Severe Thunderstorms and their Radiometric Signatures

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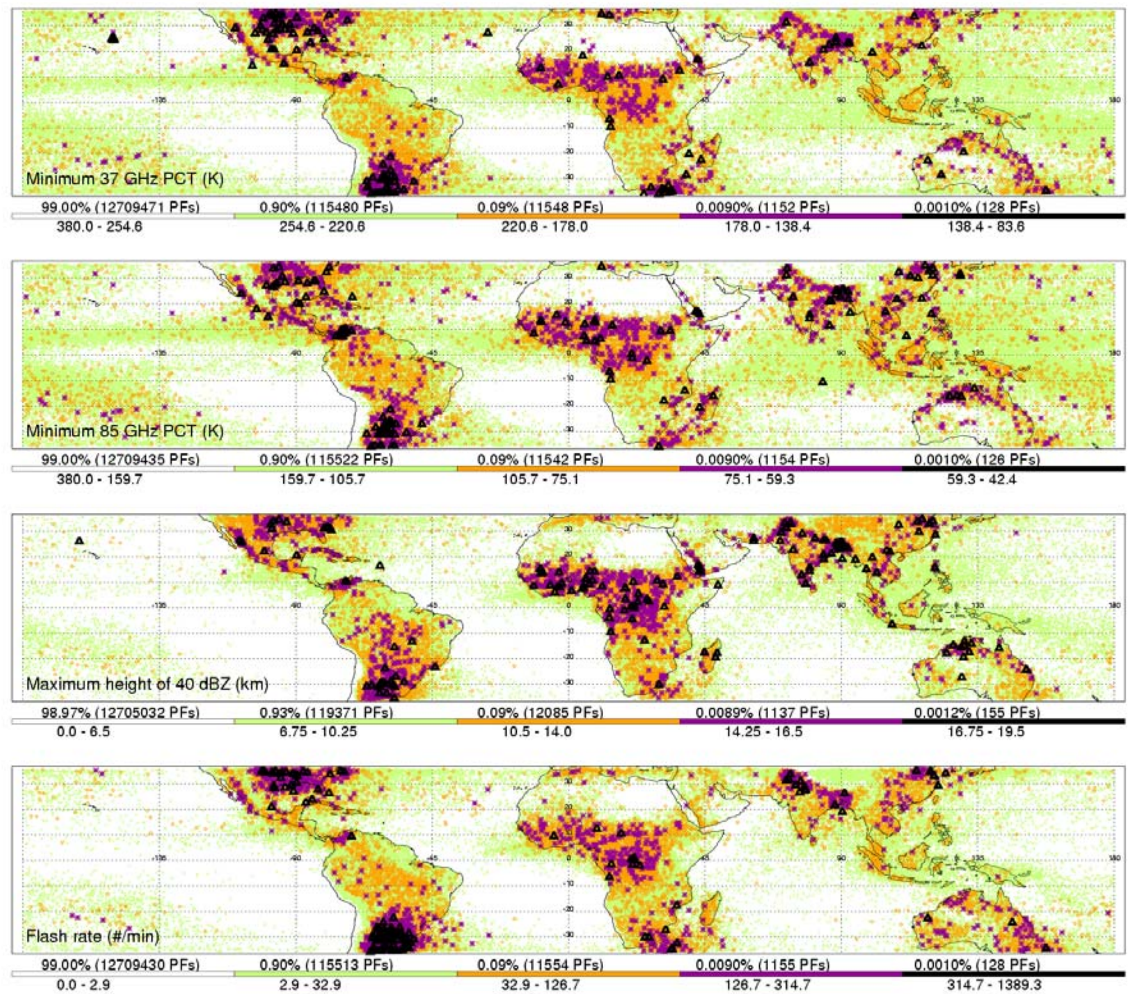
Where Are The Most Intense Thunderstorms On Earth? By Zipser, Cecil, Liu, Nesbitt, Yorty, 2006 *BAMS*

From TRMM satellite, we have several ways of inferring intense thunderstorms…

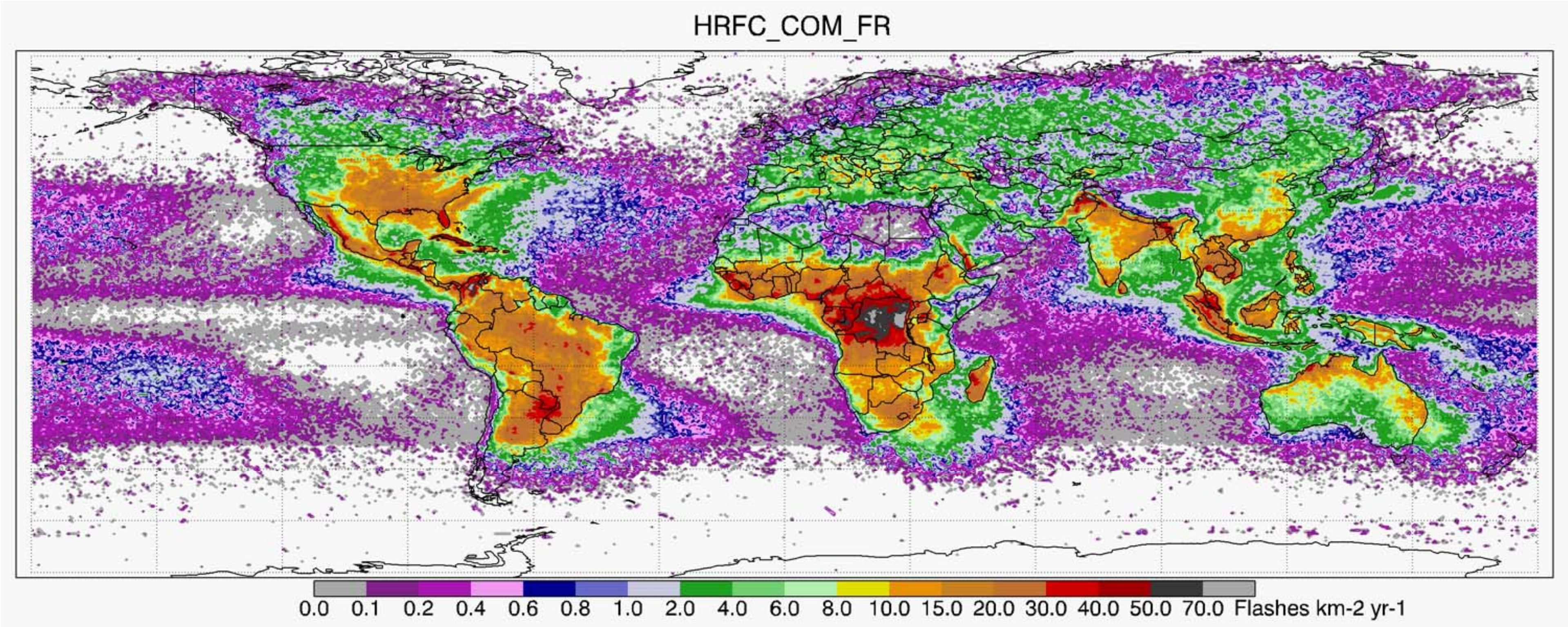
Very low passive microwave brightness temperature (top 2 panels)

High radar reflectivity well above freezing level (3rd panel)

High lightning flash rate



Total Lightning Flash Rate



1) "Lightning Loves Land"
2) Tropical land has lots of thunderstorms, but generally not the strongest storms (contrast with previous plots of extreme storms)

Outline

I. Basic background on radiative transfer as it applies to passive microwave remote sensing of thunderstorms
II. Examples from individual cases
III. Empirical identification of severe thunderstorms from satellites
IV. Climatology of severe thunderstorms from satellites

Passive Microwave Radiative Transfer
Transferência de Microondas Passiva Radiativo

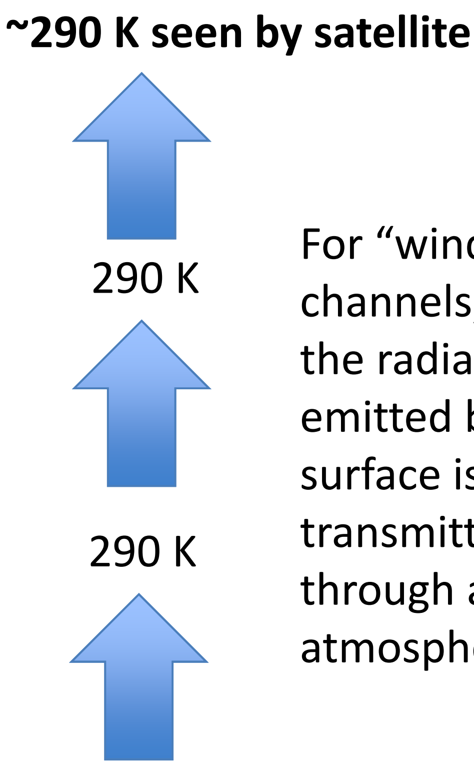
Many instruments use window channels ~ 10, 19, 37, 85 GHz to measure precipitation
TMI, GMI, AMSR-E, SSMI (no 10 GHz on SSMI)

Muitos instrumentos utilizam canais janela

A cloudless atmosphere has little effect on radiation emitted by the earth's surface

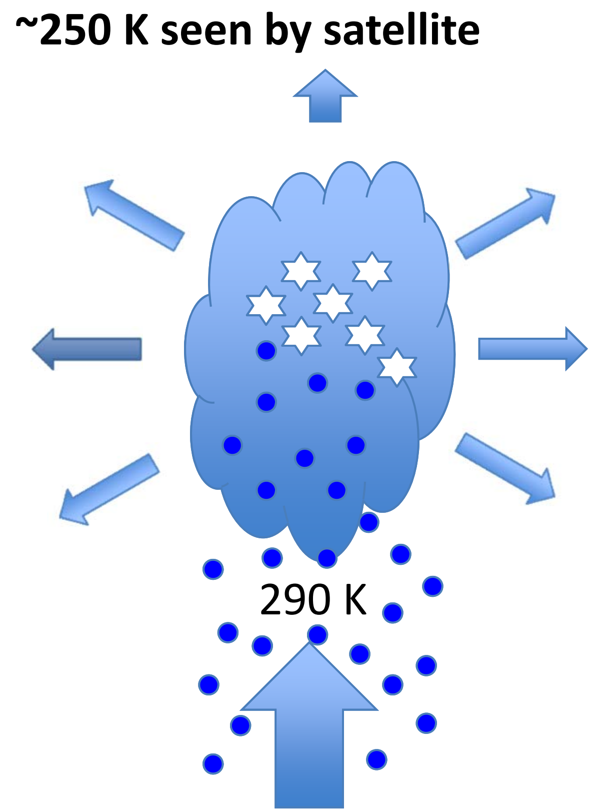
A atmosfera sem nuvens tem pouco efeito sobre a radiação emitida pela superfície da terra

Satellite Passive Microwave Over Land



For “window” channels, most of the radiation emitted by the surface is transmitted through a clear atmosphere

Clouds and rain *absorb*, *emit*, and *scatter* some of the radiation away, *reducing the brightness temperature (T_B)*



Land has high emissivity (~0.95), so upwelling brightness temperature often >290 K

Water, soil moisture, vegetation reduce the emissivity

Complex Index of Refraction (m)

- *Absorption* and *Emission* increase with the *imaginary* part of the index of refraction
- *Scattering* increases with the *real* part of the index of refraction
- Example values (don't quote me on these numbers!):

Liquid drops: $m = \mathbf{5} + (\mathbf{2 * i})$

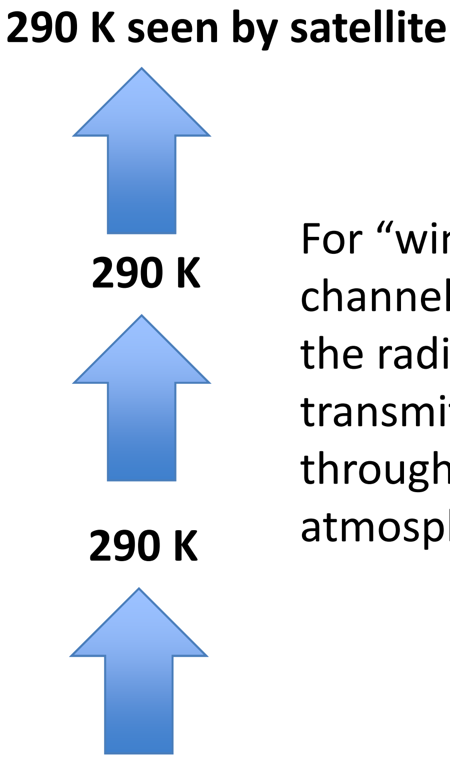
➢**Real** and **imaginary** parts comparable, so absorption, emission, and scattering comparable

Ice: $m = \mathbf{2} - (\mathbf{0.002 * i})$

➢***Imaginary*** *part is negligible, so only scattering matters for ice hydrometeors*

See Gunn and East 1954 QJRMS

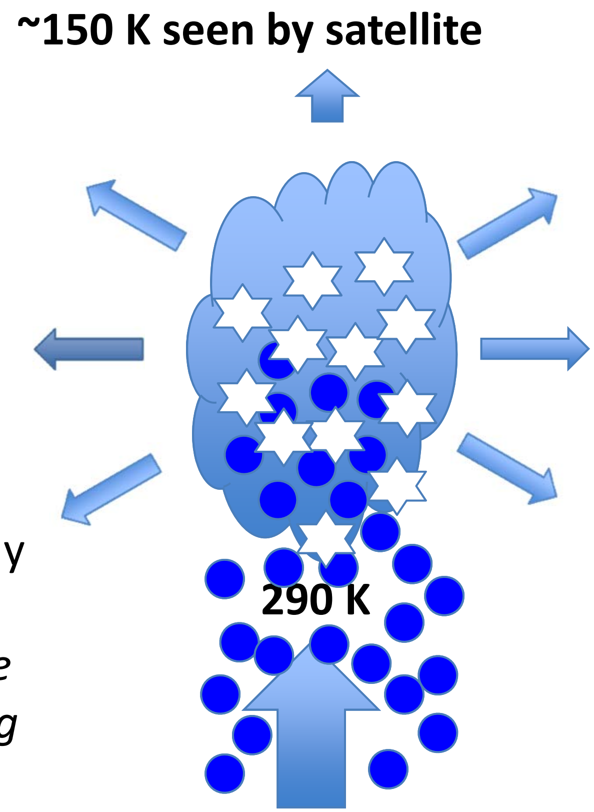
Satellite Passive Microwave Over Land



For “window” channels, most of the radiation is transmitted through a clear atmosphere

Mie scattering gets complicated, but large hydrometeors reduce the brightness temperature *(T_B)* even more.

Ice has very small absorption / emission. Ice mostly scatters radiation. *This makes ice more effective at reducing T_B.*



Land has high emissivity (~0.95), so upwelling brightness temperature often >290 K
Water, soil moisture, vegetation reduce the emissivity

Radiative Transfer in Precipitation

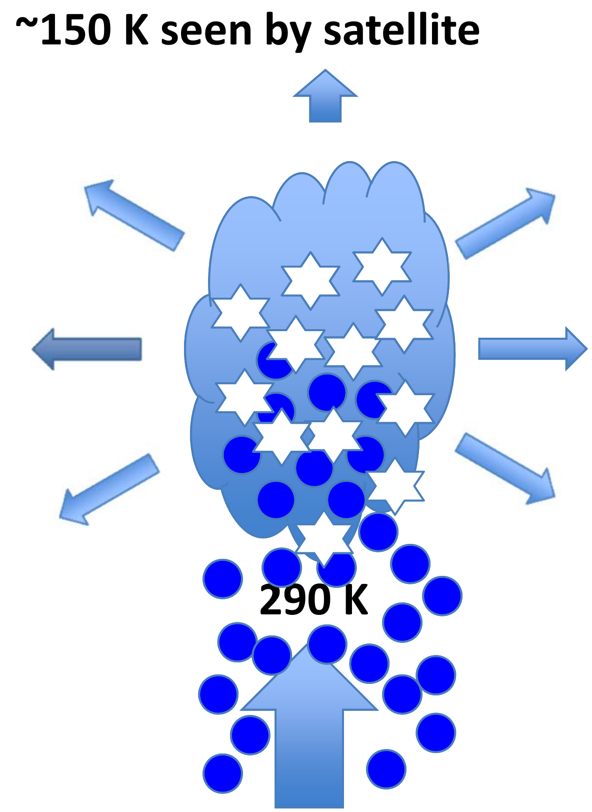
Some fraction of the radiation emitted by the surface passes through the atmosphere unaffected.

Liquid drops absorb radiation, and emit at their own temperature ($T_{raindrop} < T_{surface}$).

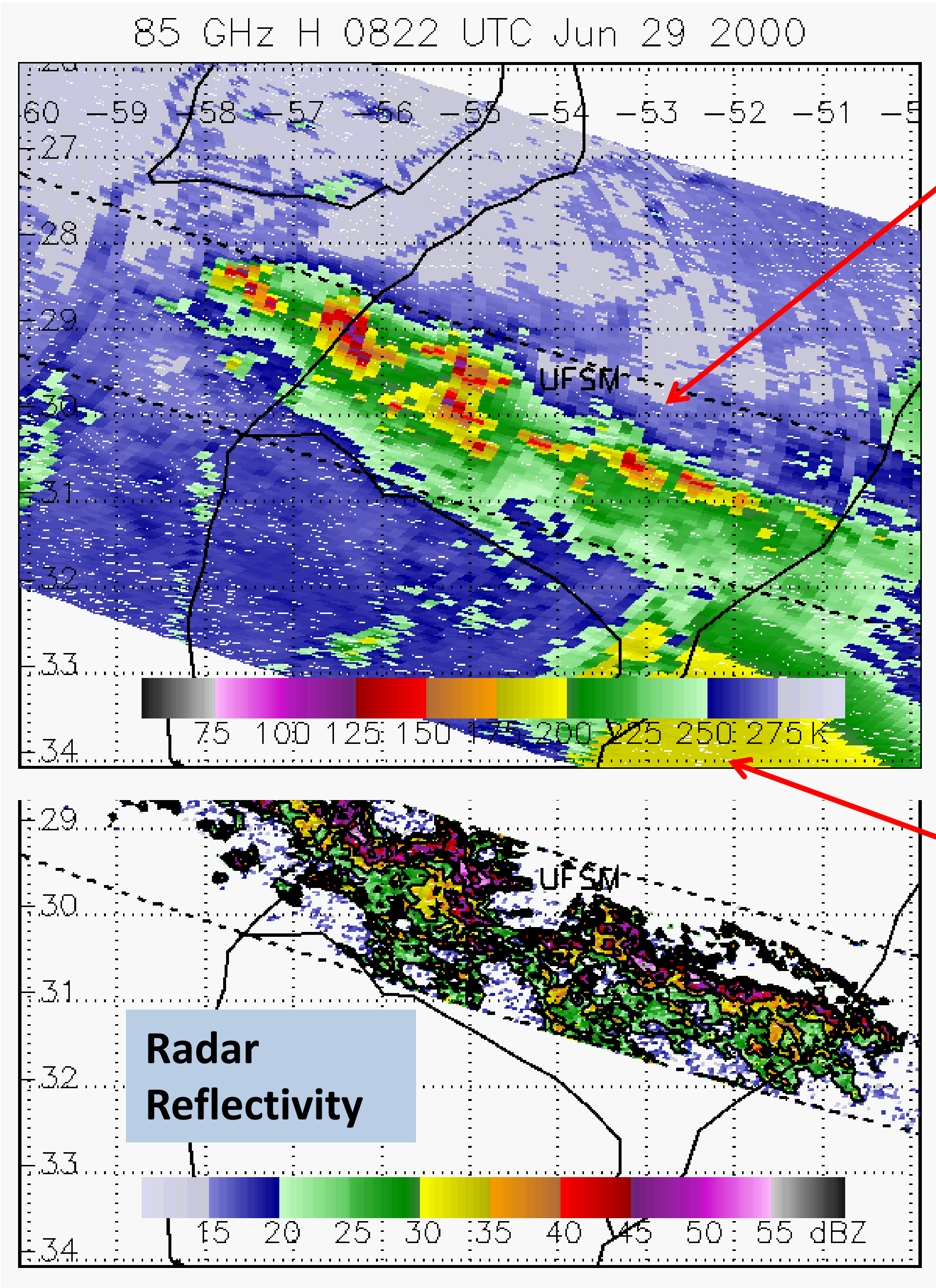
Liquid and ice hydrometeors (graupel, hail) scatter radiation in all directions.

Larger, denser particles have greater effect.

Scattering cross section ~ size and density



Example: 85 GHz TB (Horizontal Polarization)

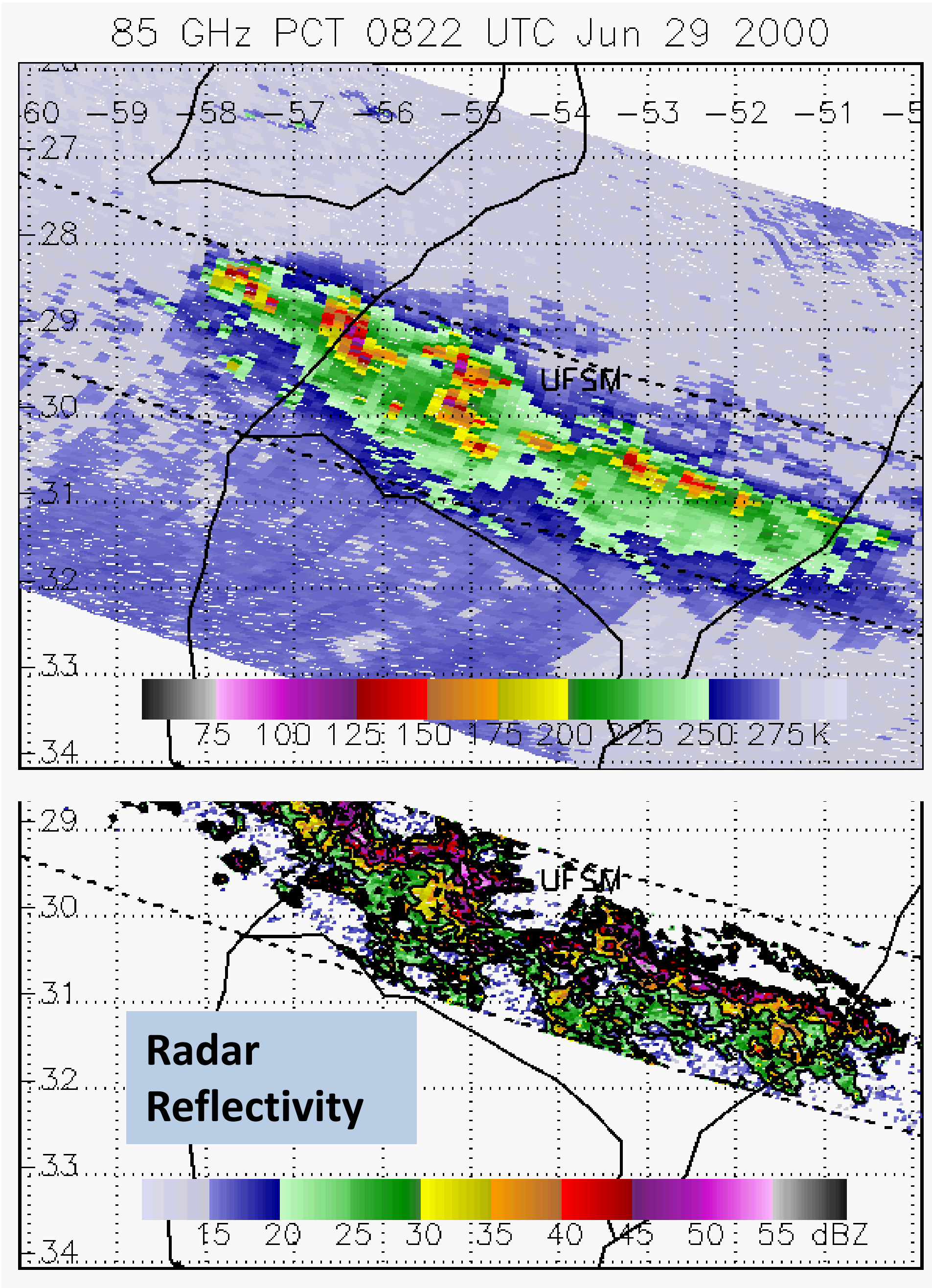


TB decreases in raining locations, matches radar echo reasonably well

Away from rain, TB has variability due to surface conditions (e.g. wetness)

Ocean surface has lower emissivity than land, so TB is lower over ocean (unless there is cloud & rain)

Example: 85 GHz Polarization Corrected Temperature (PCT)



A linear combination of the Horizontal and Vertical polarizations removes much of the variability due to surface conditions. This is Polarization Corrected Temperature (PCT).

$PCT_{85} = 1.82\ TB_{85V} – 0.82\ TB_{85H}$

$PCT_{37} = 2.20\ TB_{37V} – 1.20\ TB_{37H}$

(from Cecil et al. 2002 Mon Wea Rev)

Microwave Frequencies

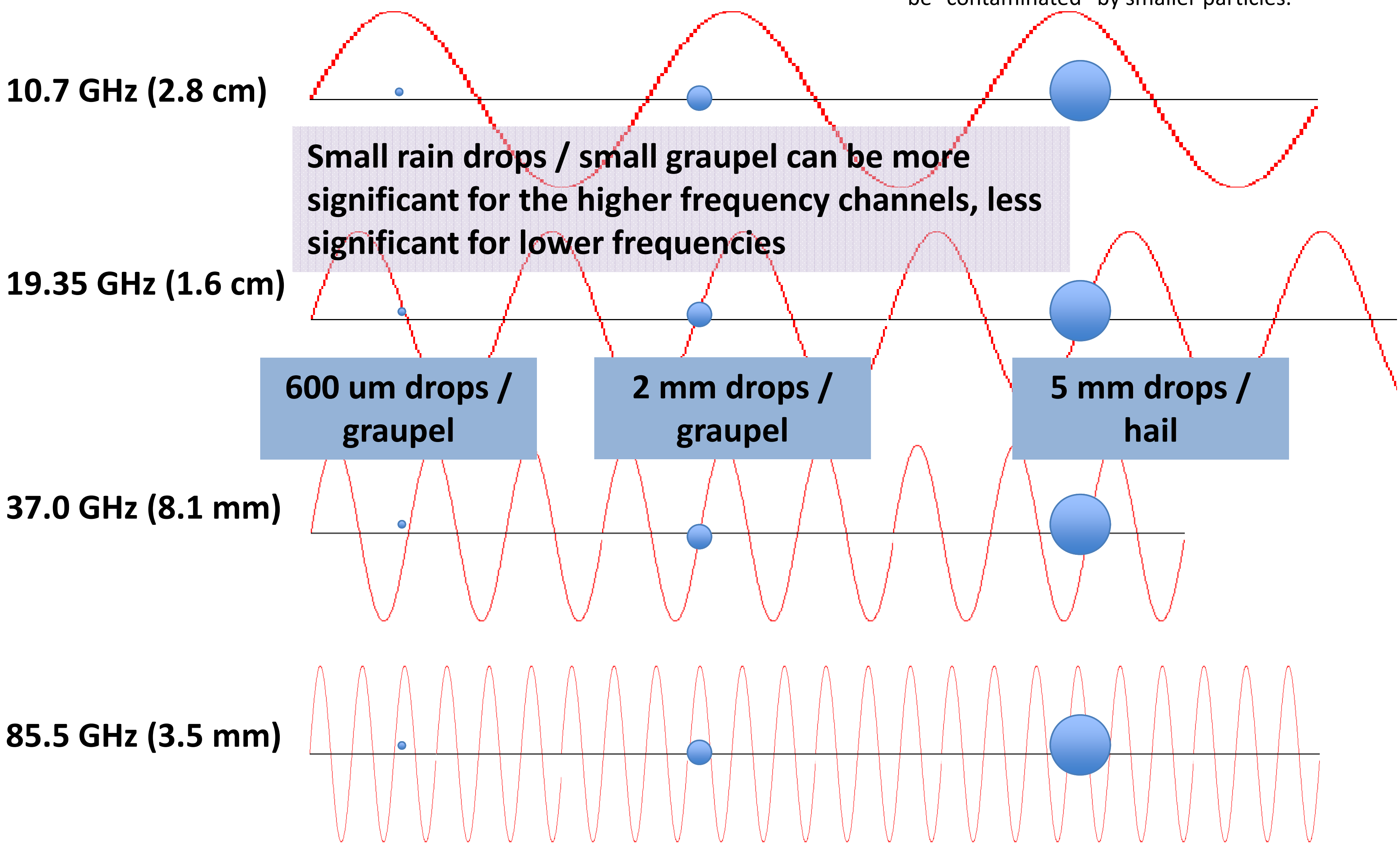
- Considering the Radiative Transfer alone, we would want a low frequency channel for sensitivity to large particles that are produced by strong thunderstorms. Higher frequencies can be "contaminated" by smaller particles.

- But lower frequencies have larger beam sizes. For TRMM satellite:
  - 10 GHZ channel: 63 km x 37 km (~size of a county)
  - 19 GHz channel: 30 km x 18 km (~size of Corpus Christi Bay)
  - 37 GHz channel: 16 km x 9 km
  - 85 GHz channel: 7 km x 5 km (~size of a thunderstorm)

- So there is a trade-off. 37 GHz channel works well for identifying severe storms.

Common Radiometer Frequencies

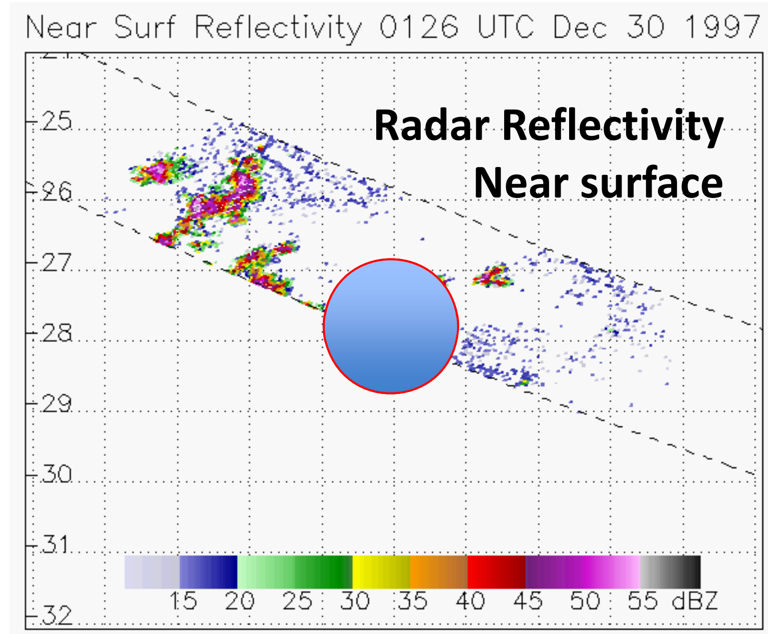
Considering the Radiative Transfer alone, we would want a low frequency channel for sensitivity to large particles that are produced by strong thunderstorms. Higher frequencies can be “contaminated” by smaller particles.

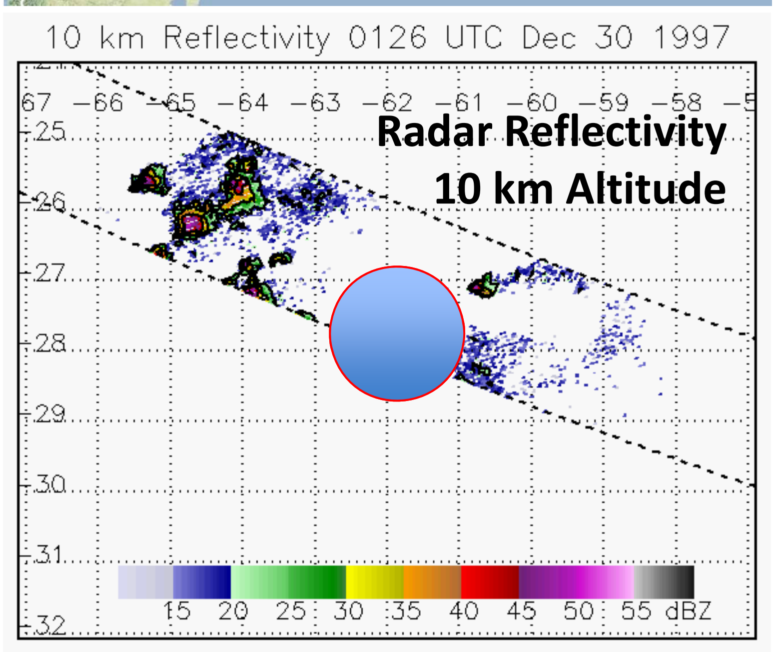


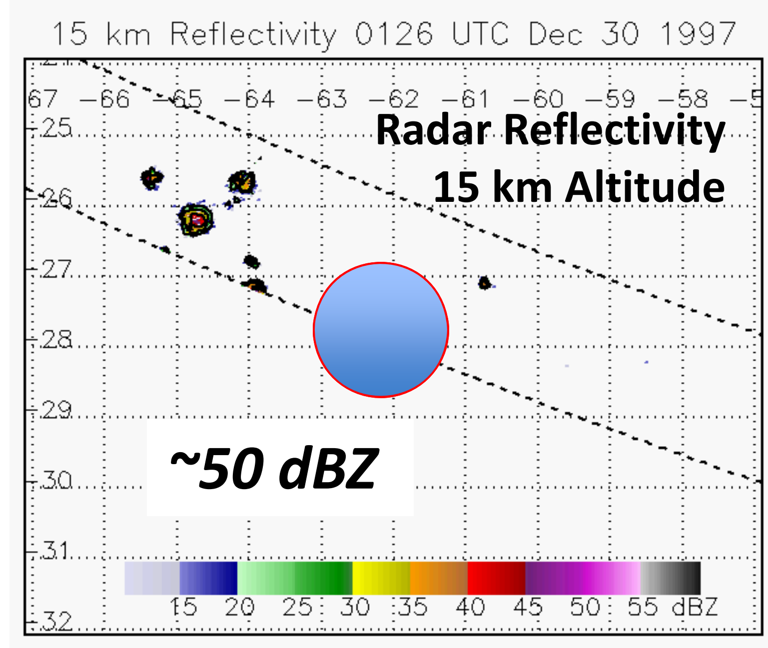
Beam-Filling Effect (Horizontal Resolution)

- As a very rough estimate of the "beam-filling effect", we can average the high-resolution 85 GHz over a large enough area to match the low-resolution channels
  - 10 GHz footprint: 63 km x 37 km $\longrightarrow$ Mean 85 GHz: 131 K
  - 19 GHz footprint: 30 km x 18 km $\longrightarrow$ Mean 85 GHz: 61 K
  - 37 GHz footprint: 16 km x 9 km $\longrightarrow$ Mean 85 GHz: 55 K
  - 85 GHz footprint: 7 km x 5 km $\longrightarrow$ Actual 85 GHz: 45 K
- So there is a trade-off. 37 GHz channel works well for identifying severe storms from the available satellite sensors.

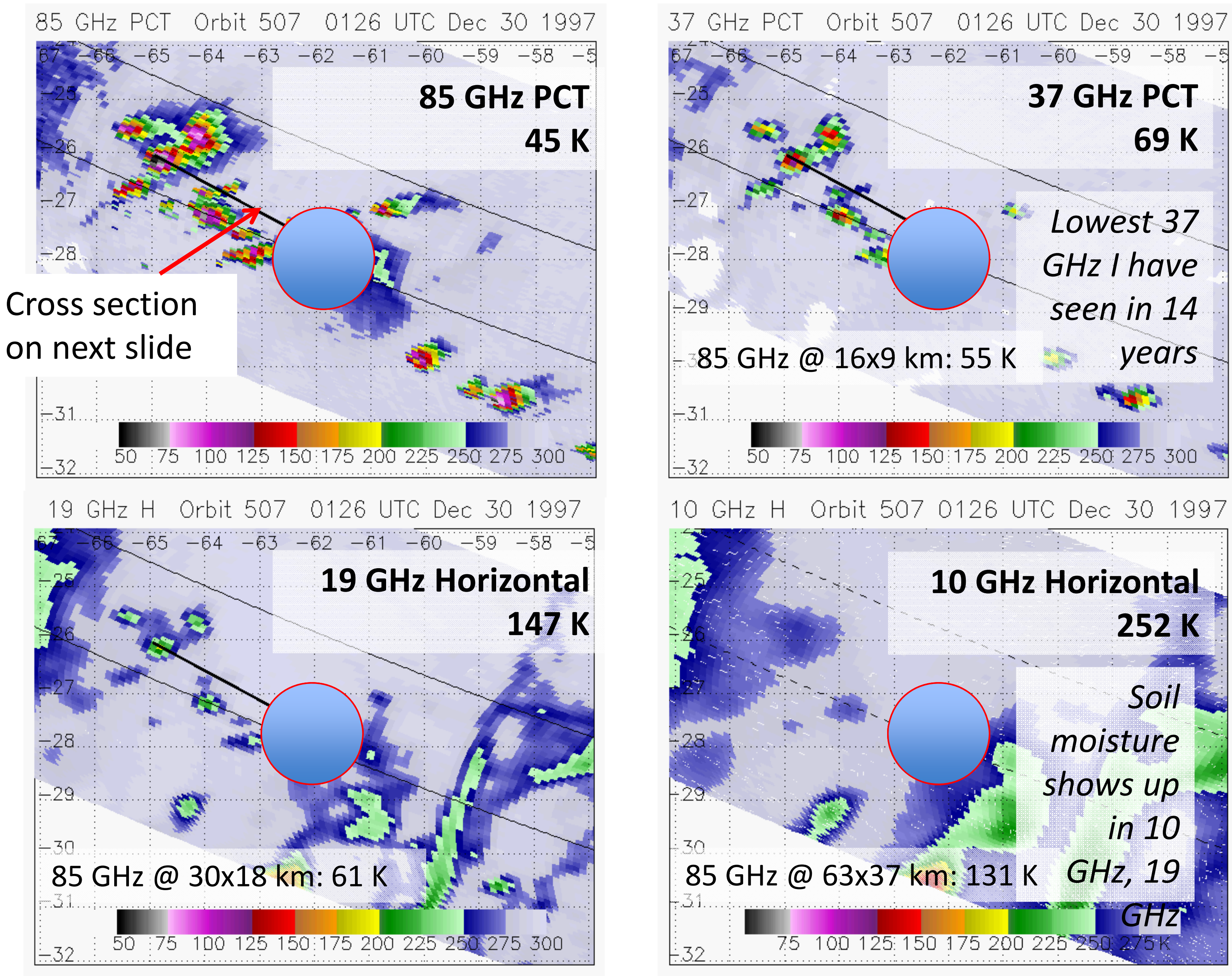
Example TRMM observations, northern Argentina



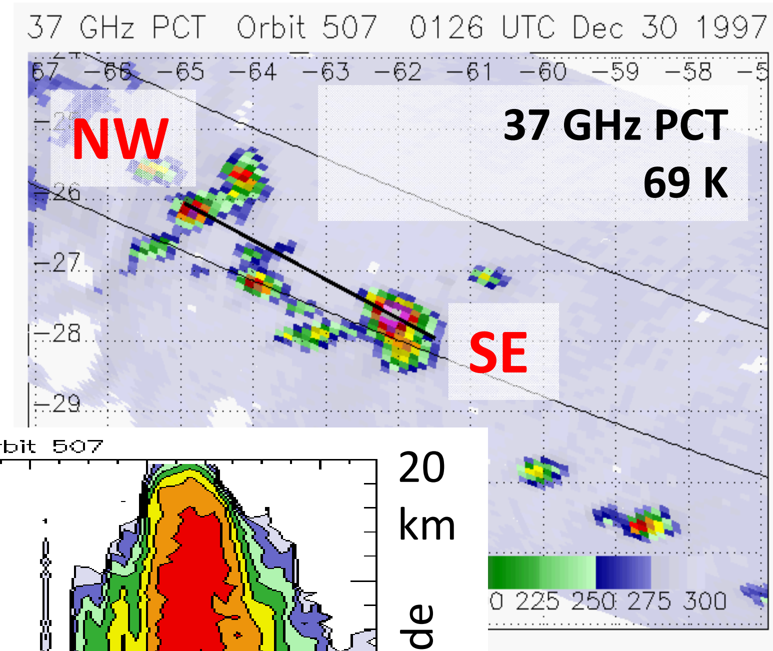




Example TRMM observations, northern Argentina

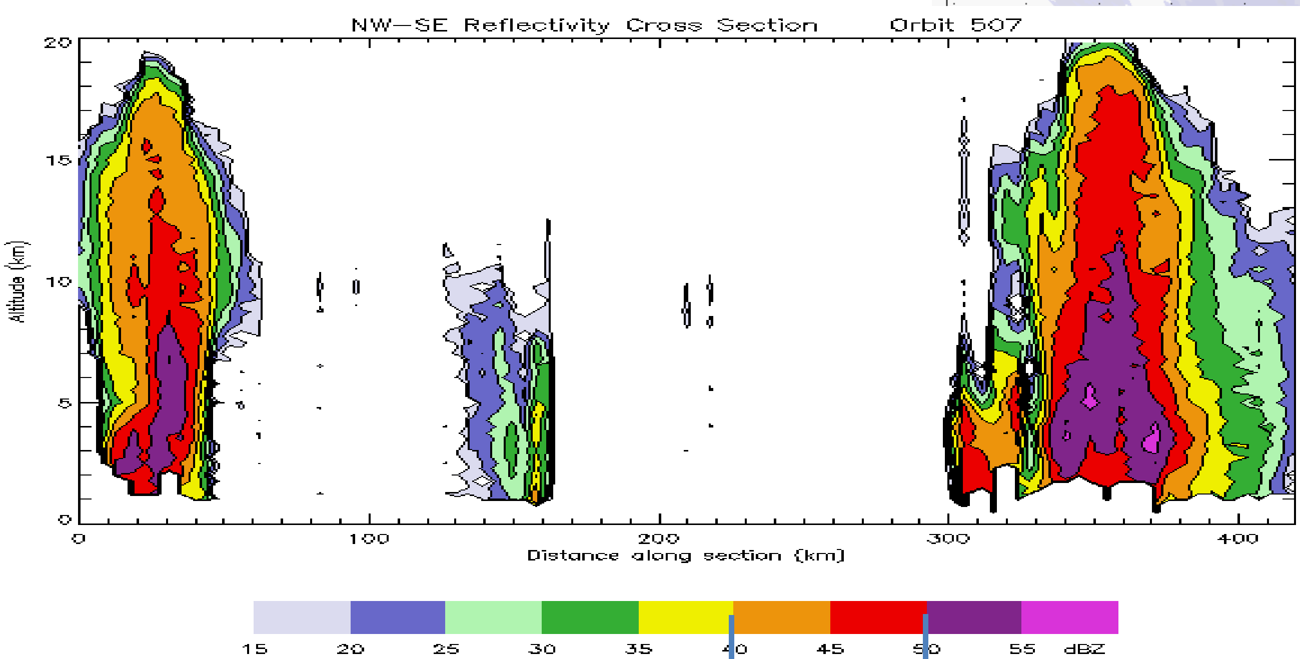


Radar Reflectivity Cross Section



50 dBZ @ ~12 km
45 dBZ @ ~18 km

NW

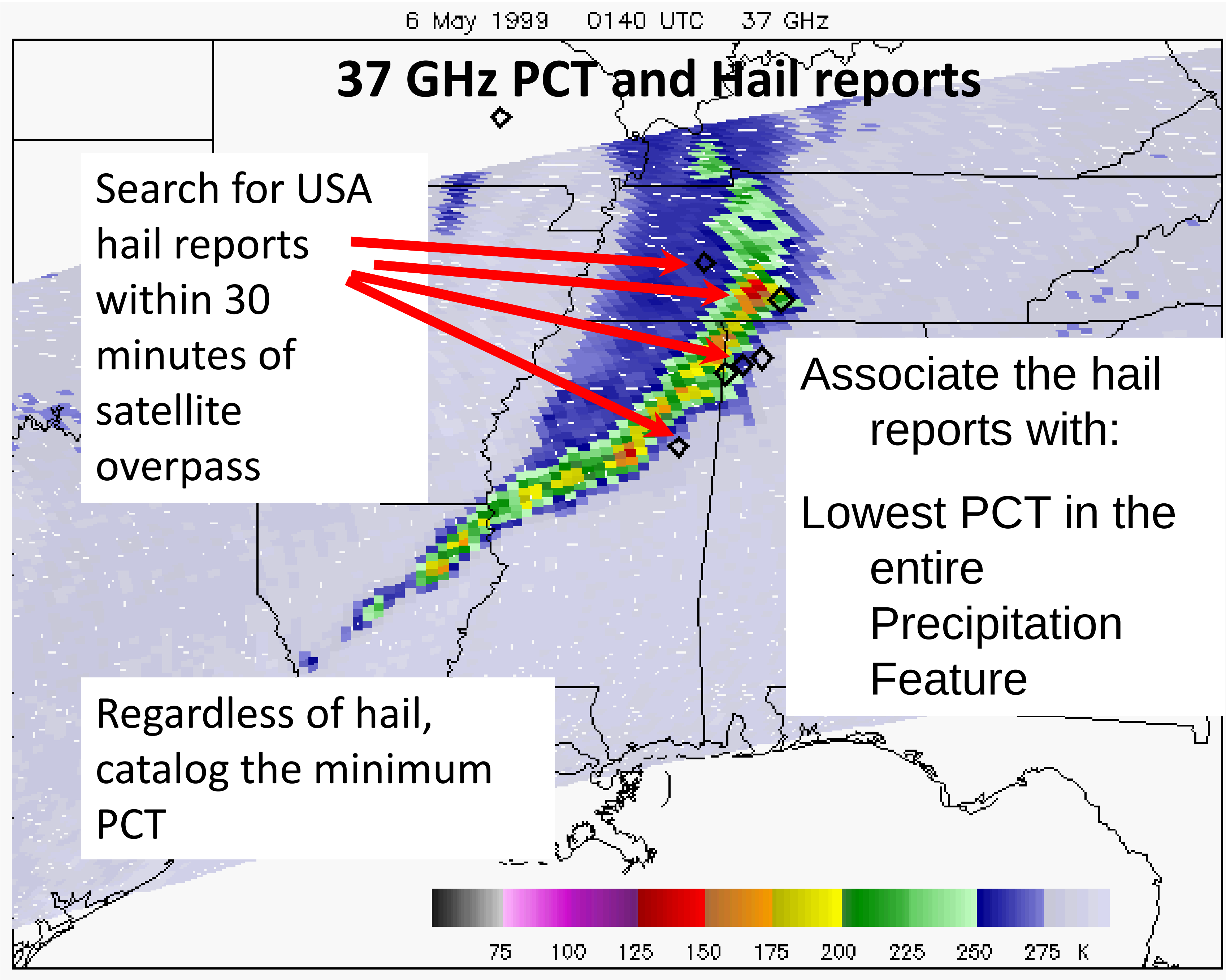


20 km altitude

SE

40 dBZ 50 dBZ

37 GHz PCT and Hail reports



Search for USA hail reports within 30 minutes of satellite overpass

Associate the hail reports with:

Lowest PCT in the entire Precipitation Feature

Regardless of hail, catalog the minimum PCT

Probability of Hail, as a function of PCT37 or PCT85

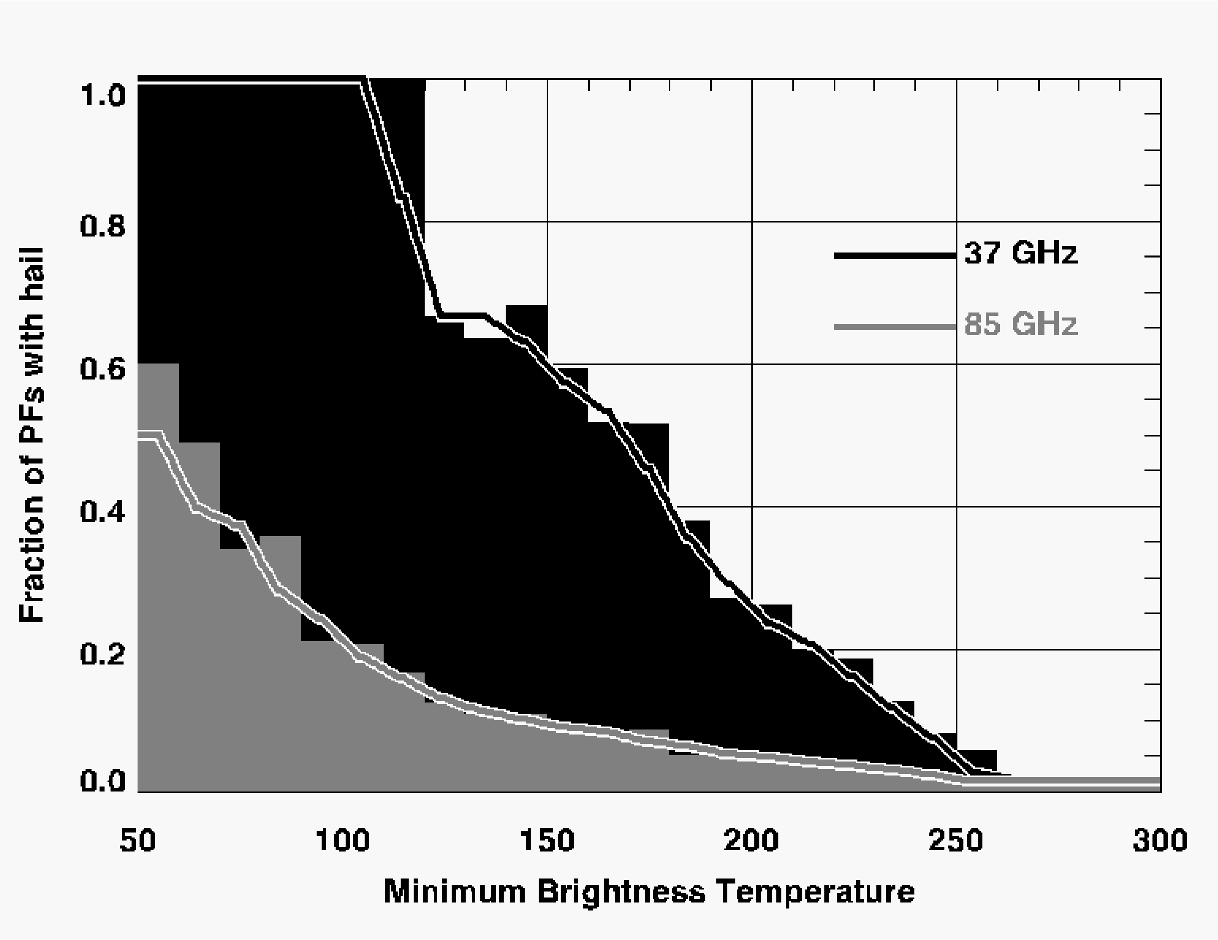
Empirically match USA reports of large hail > 2.5 cm with measurements of low PCT85 and PCT37

PCT37 = 200 K : ~25% chance of large hail

PCT37 = 150 K: ~60% chance of large hail

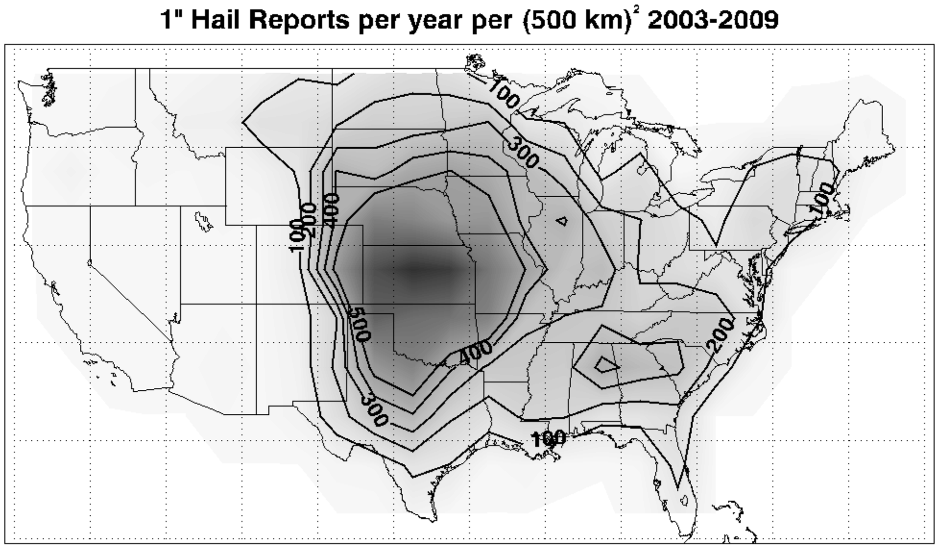
PCT37 < 120 K: all cases had large hail in this study

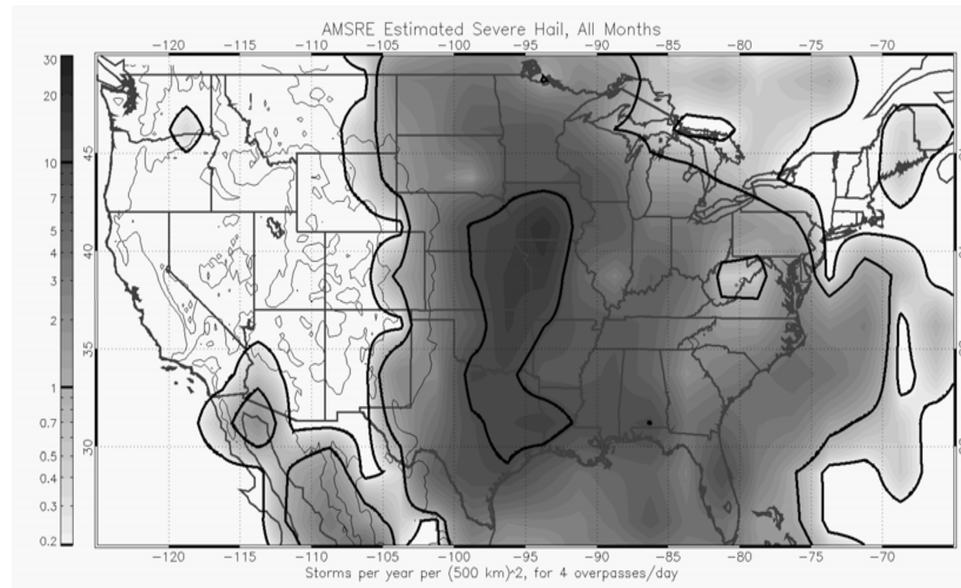
PCT85 less responsive to large hail than PCT37



Validation

For each storm with 36 GHz < 200 K, count it as a fraction (F) of one hail storm. The value F comes from the previous slide. E.g., a storm with 200 K is counted as 0.25 hail storms. A storm with 150 K is counted as 0.6 hail storms.





Reports of hail 2.5 cm diameter or larger at the surface, 2003-2009

Satellite-based estimate

Recap

- Large hydrometeors, especially graupel and hail, reduce the passive microwave brightness temperatures seen by satellite sensors such as TRMM, GPM, AMSR-E, SSMI
- 37 GHz Polarization Corrected Temperature (PCT) < 200 K has ~20% likelihood of large hail.

  < 150 K, ~60%

  < 130 K *approaches* 100 %

  These are empirically derived using 2.5+ cm hail reports in USA

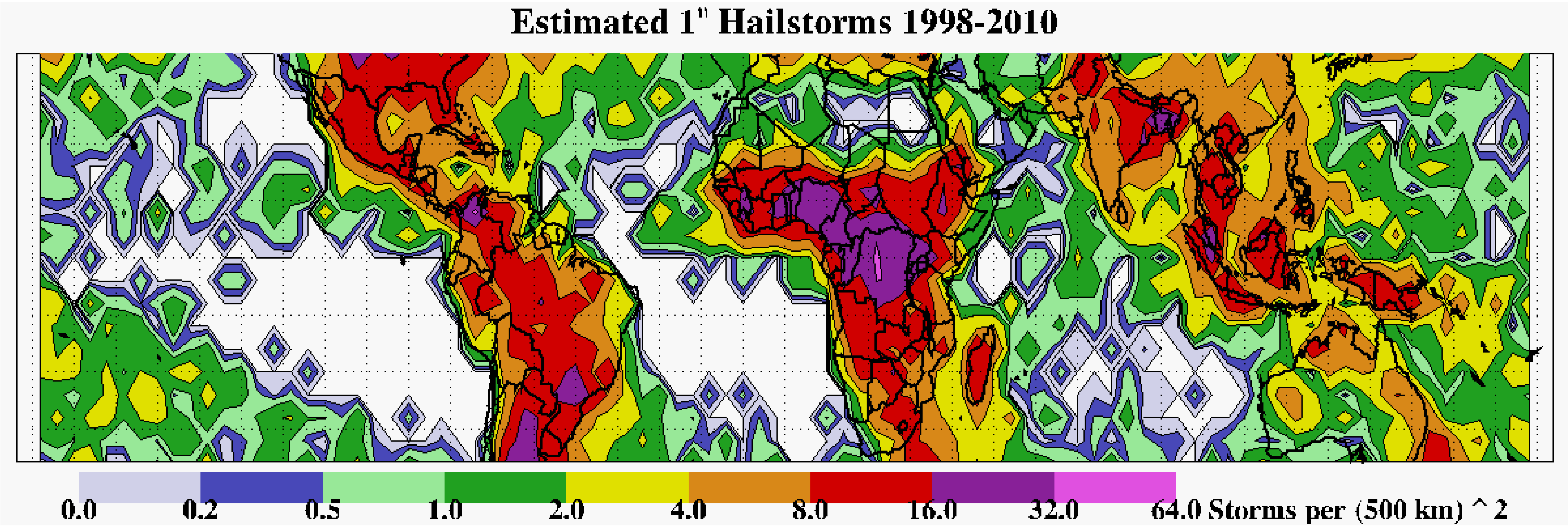
Coming up next…

- We can apply the same basic methodology to a few different types of measurements: PCT85, PCT37, Radar Reflectivity at different altitudes, lightning flash rate, et cetera

- We get different answers from each measurement type, because none of them are directly measuring what we want – large hail that falls to the surface

- But they all identify the same basic locations: Argentina, Paraguay, Uruguay, Southern Brazil, Central and Southeast USA, Bangladesh, East and West India, Pakistan, Central Africa…

Empirical relationship applied to all TRMM 37 GHz PCT



From this approach, Central Africa has the most storms. But stay tuned, this answer will change.

Other common locations:

Subtropical Americas

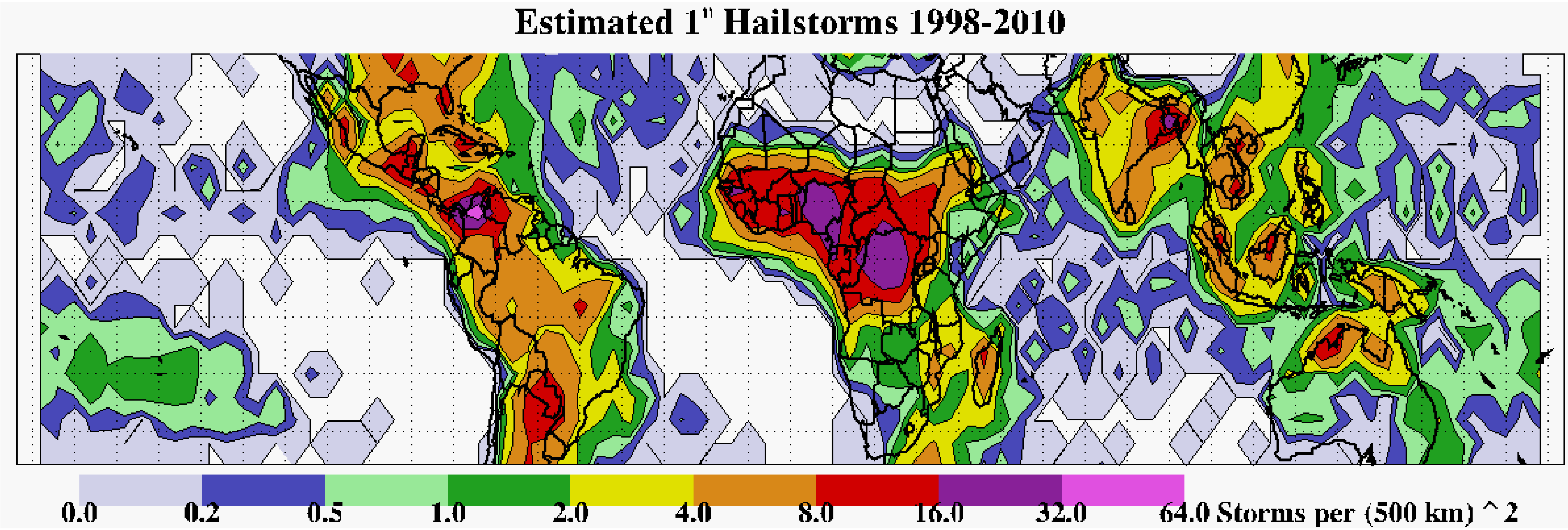
Bangladesh

Northern Colombia

Indonesia

These estimates are probably too high over oceans

Empirical relationship applied to all TRMM 85 GHz PCT



From this approach, Northern Colombia has the most storms. But 85 GHz is more likely to be influenced by a very deep layer of moderate-sized particles, instead of very large particles.

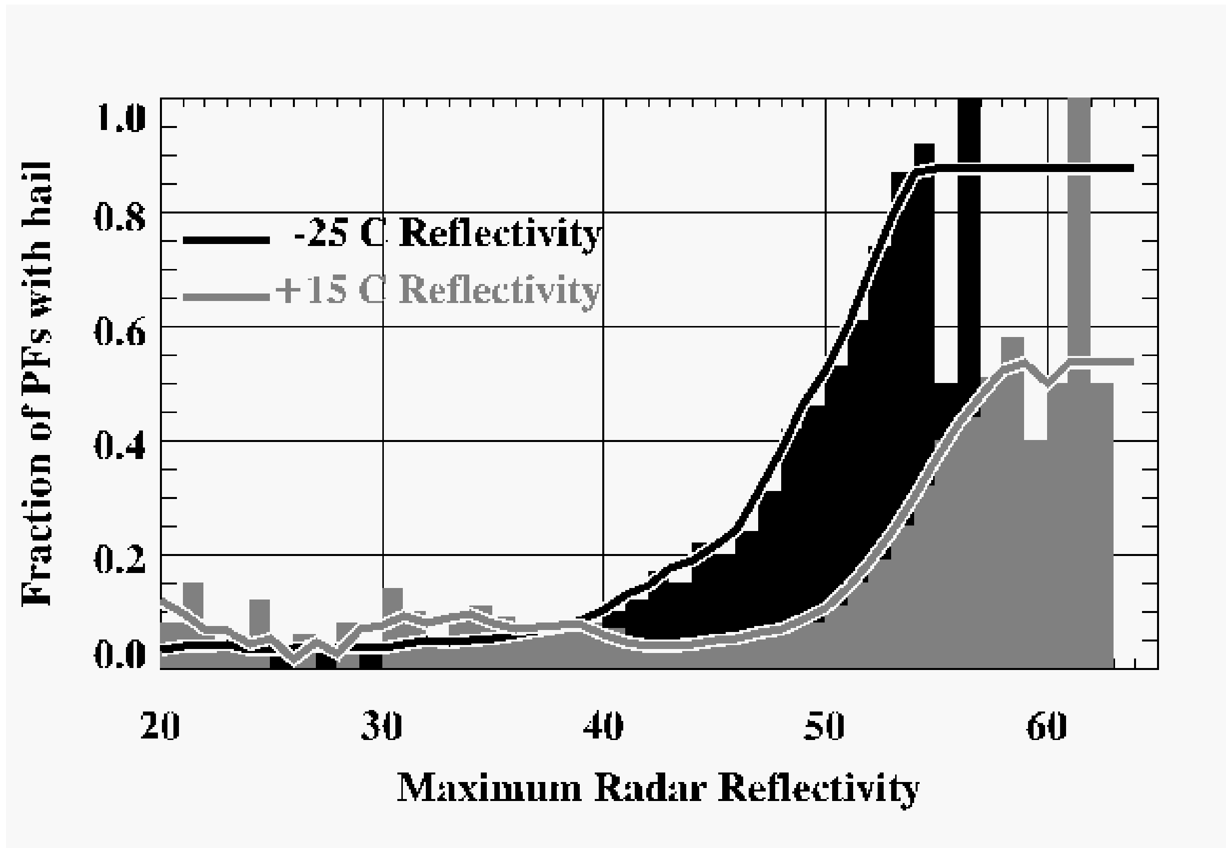
Probability of Hail, as a function of Radar Reflectivity at -25 C (black) or at +15 C (gray)

Empirically match USA reports of large hail > 2.5 cm with measurements of high radar reflectivity

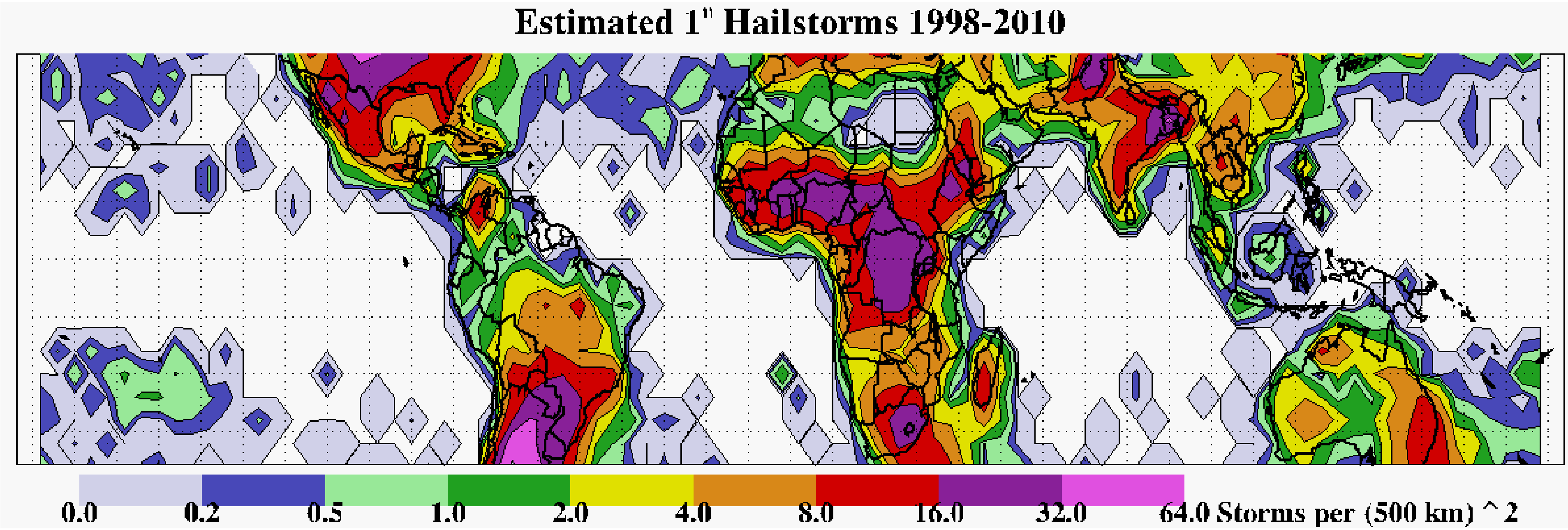
45 dBZ @ -25 C: ~20% chance of large hail

50 dBZ @ -25 C: ~50% chance of large hail

Low-altitude reflectivity is less indicative of hail, it could have high reflectivity due to large liquid rain drops



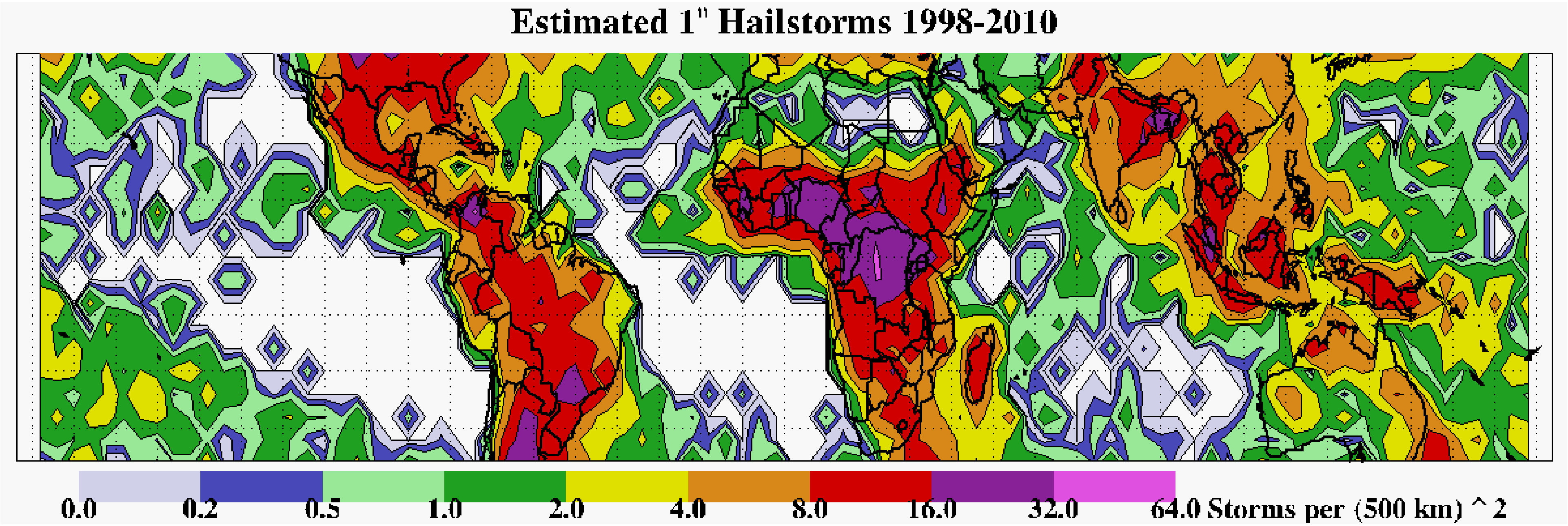
Empirical relationship applied to all TRMM Radar Reflectivity @ -25 C altitude



From this approach, Argentina has the most storms. This looks most realistic, compared to expectations (especially over oceans).

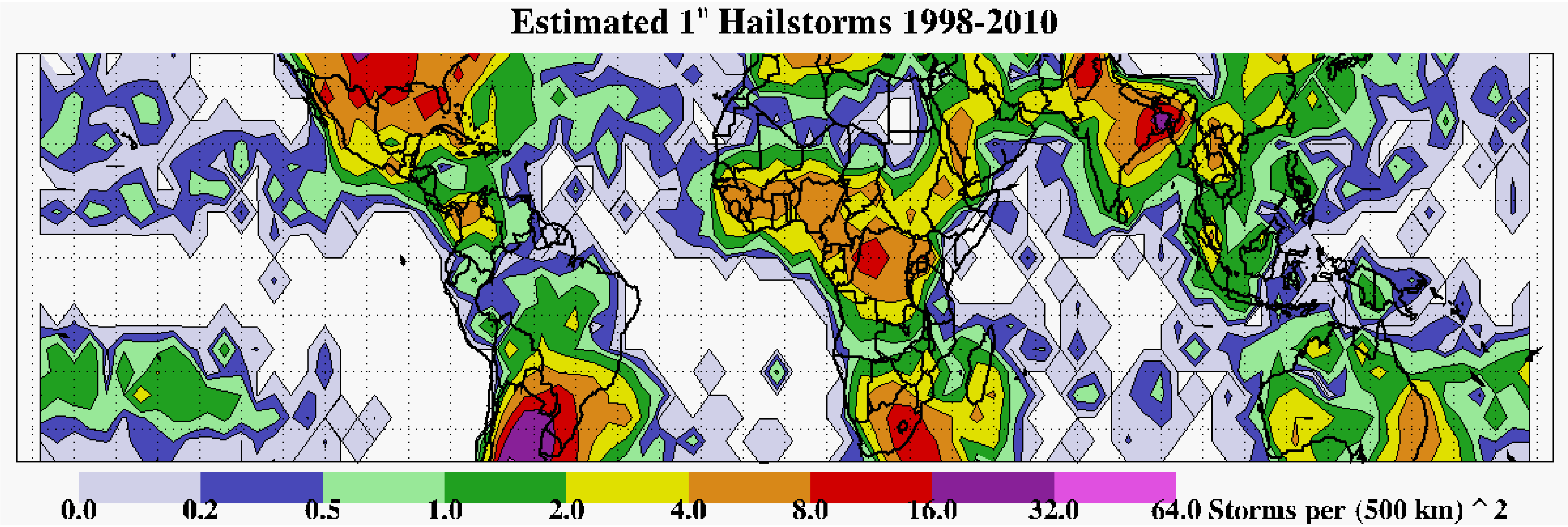
Compared to the 37 GHz- and 85 GHz-based results, using radar data drastically decreases the storm counts in deep tropics.

Empirical relationship applied to all TRMM 37 GHz PCT



(Toggle back and forth for comparison)

Empirical relationship applied to all TRMM Radar Reflectivity @ +15 C altitude

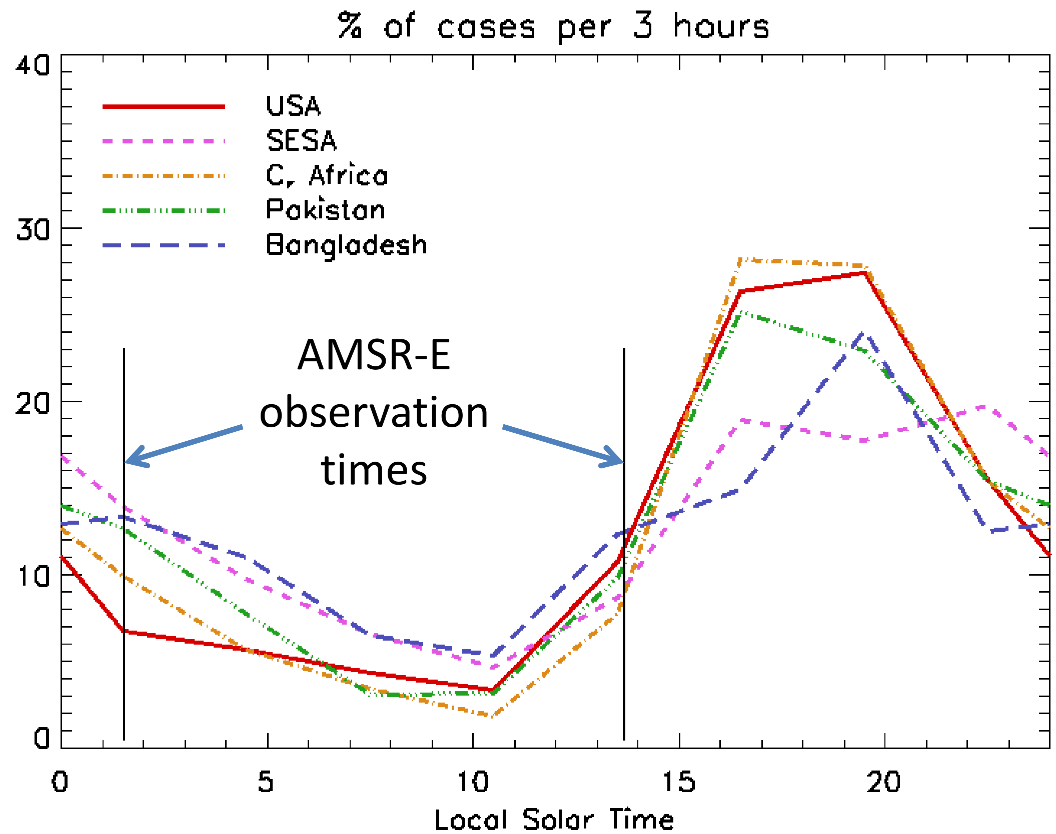


This approach again favors Argentina. But using low-altitude reflectivity puts too many storms over the oceans, likely having high reflectivity from strong liquid rain.

Hail diurnal cycle from TRMM

Typical diurnal cycle peaks in late afternoon - evening (I.e., out of phase with AMSR-E sensor that is used in upcoming figures).

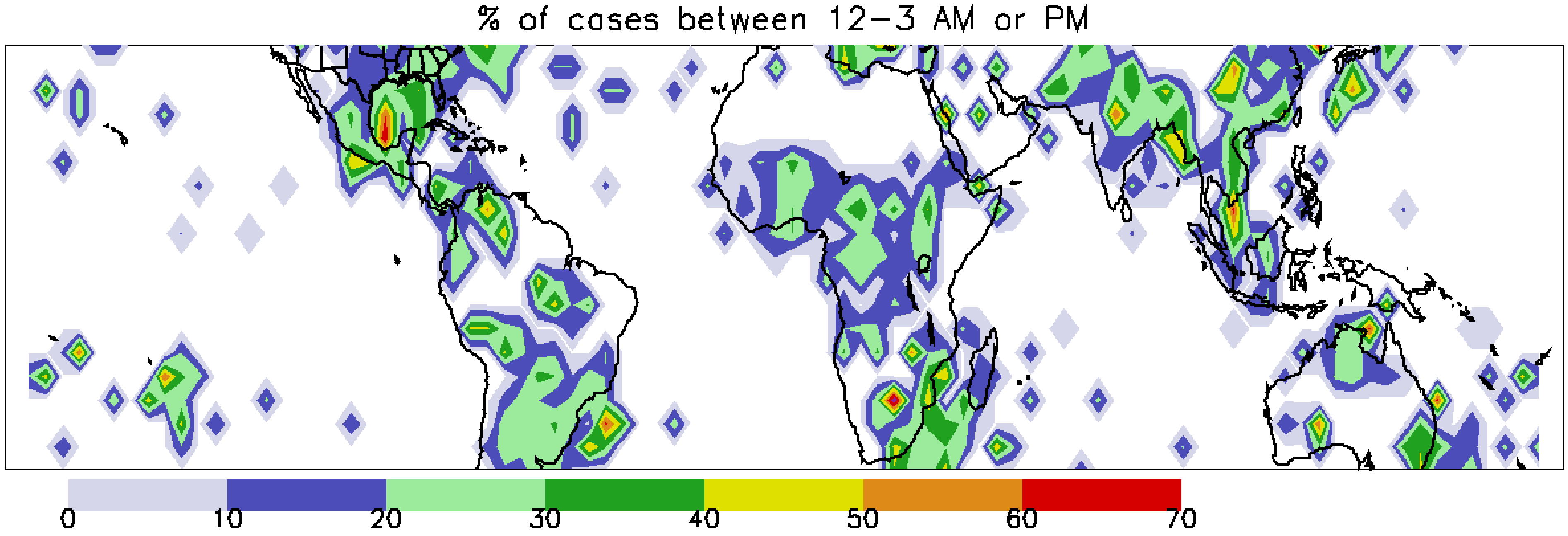
Amplitude of diurnal cycle appears weaker in SE South America than in other locations. More overnight storms here.



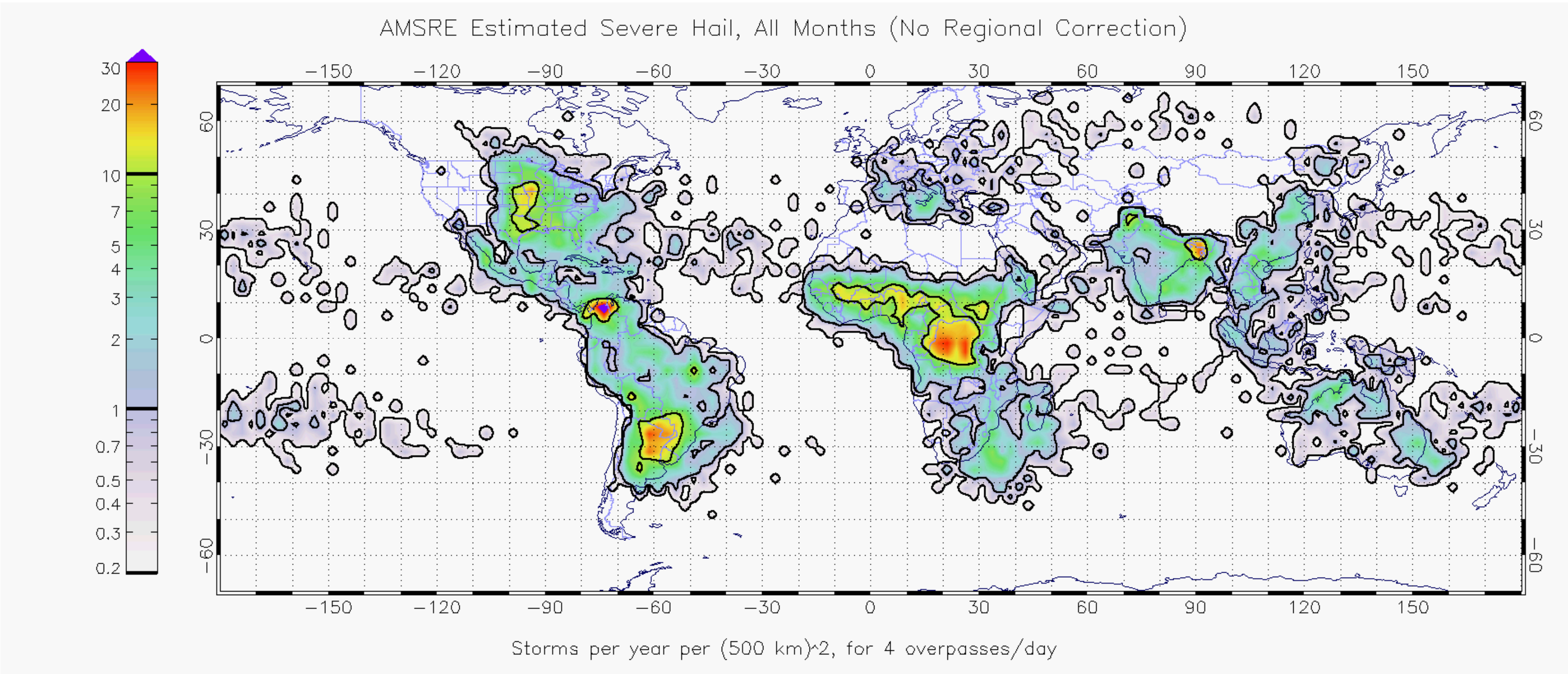
Hail diurnal cycle from TRMM

Places with strongest diurnal cycles should be under-represented by AMSR-E.

SE S. America, Bangladesh have weakest diurnal cycles of the active regions in TRMM domain. They may be over-represented.

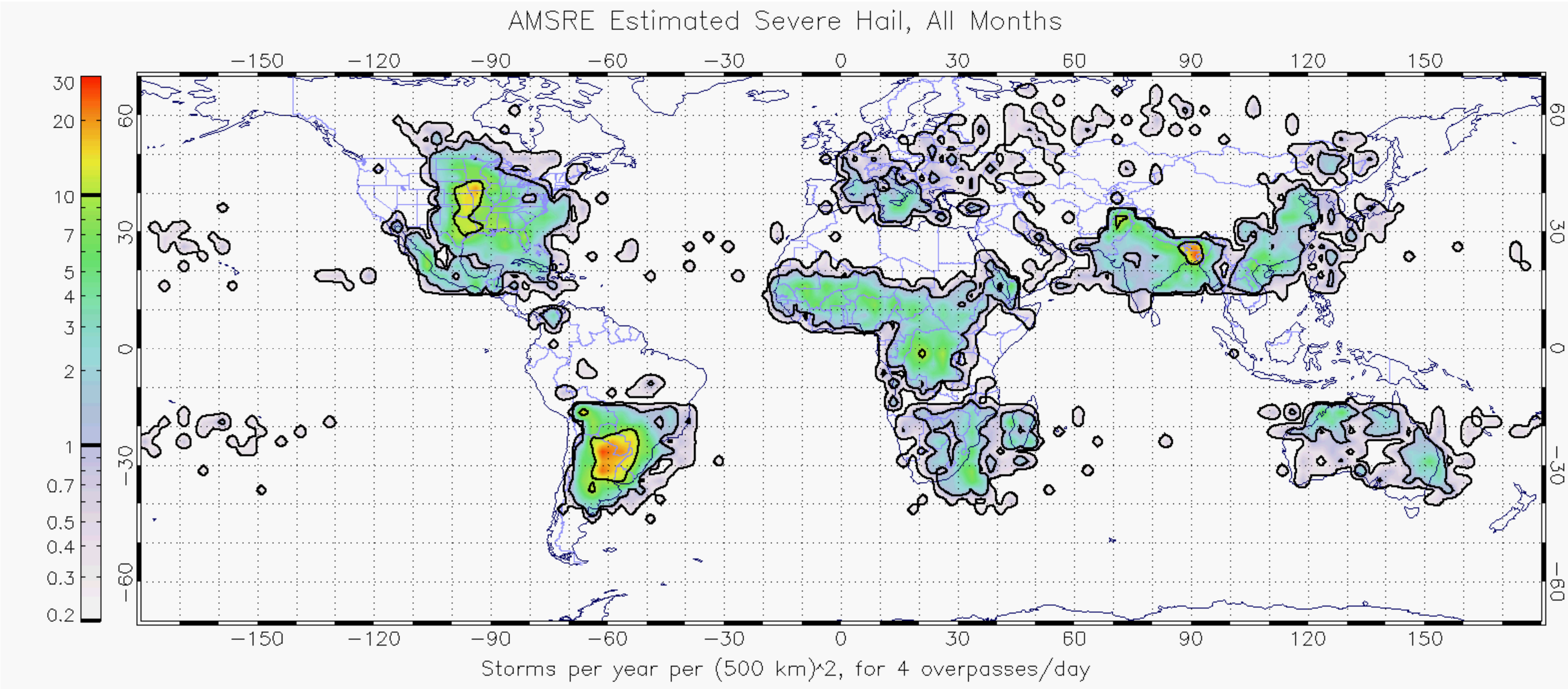


Empirical relationship applied to all AMSR-E 36 GHz PCT (includes high latitudes)



Using AMSR-E has the benefit of higher-latitude observations, especially helpful for the Central USA, Europe, and Russia. AMSR-E is limited to a small part of diurnal cycle, around 0130 and 1330 local solar time

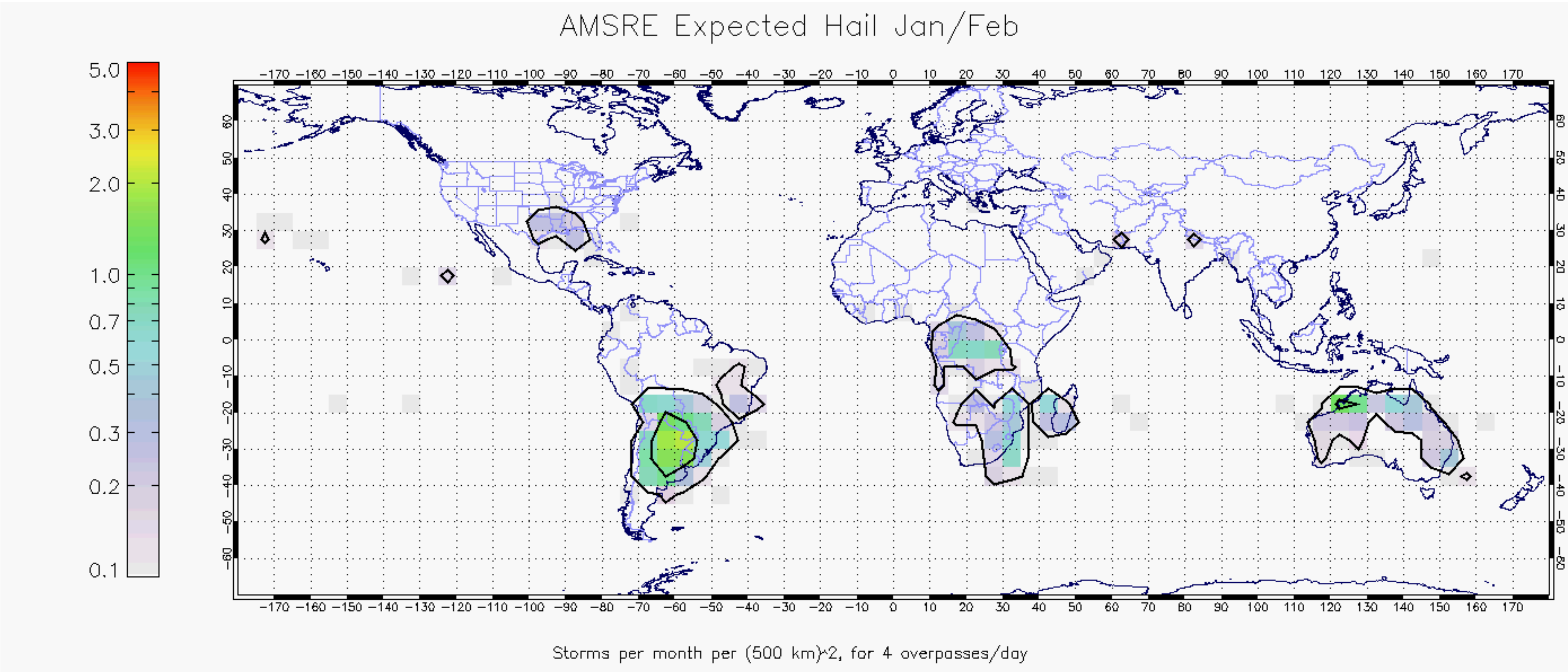
AMSR-E 36 GHz with scaling applied to tropics and oceans



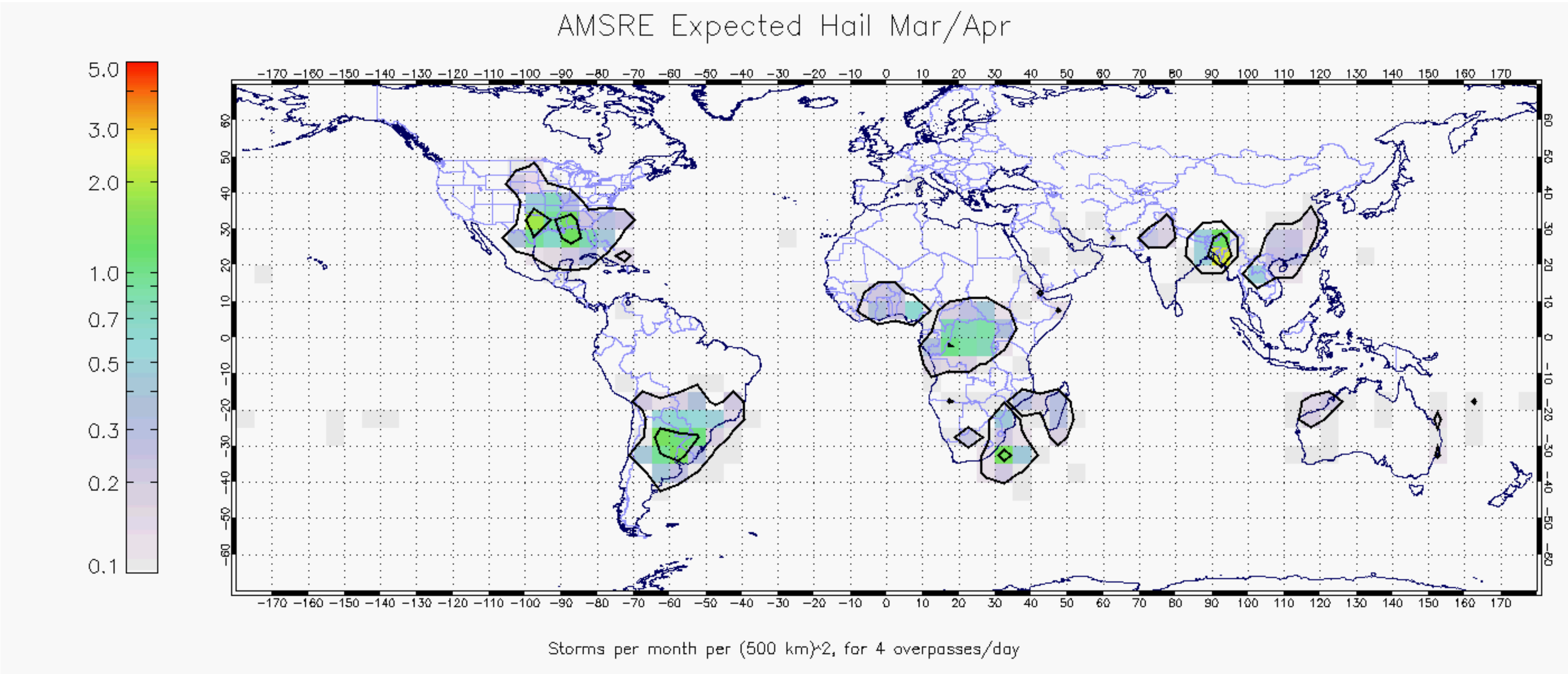
Based on regional comparisons between TRMM radar and TRMM Microwave Imager, we scaled the tropics and oceanic regions to have lower values. Cecil and Blankenship (2011) J. Appl. Meteor. Clim.

This map is our current best estimate for severe hail storm locations. Cecil and Blankenship (2012) J. Climate. Argentina and Bangladesh are essentially tied for 1st place.

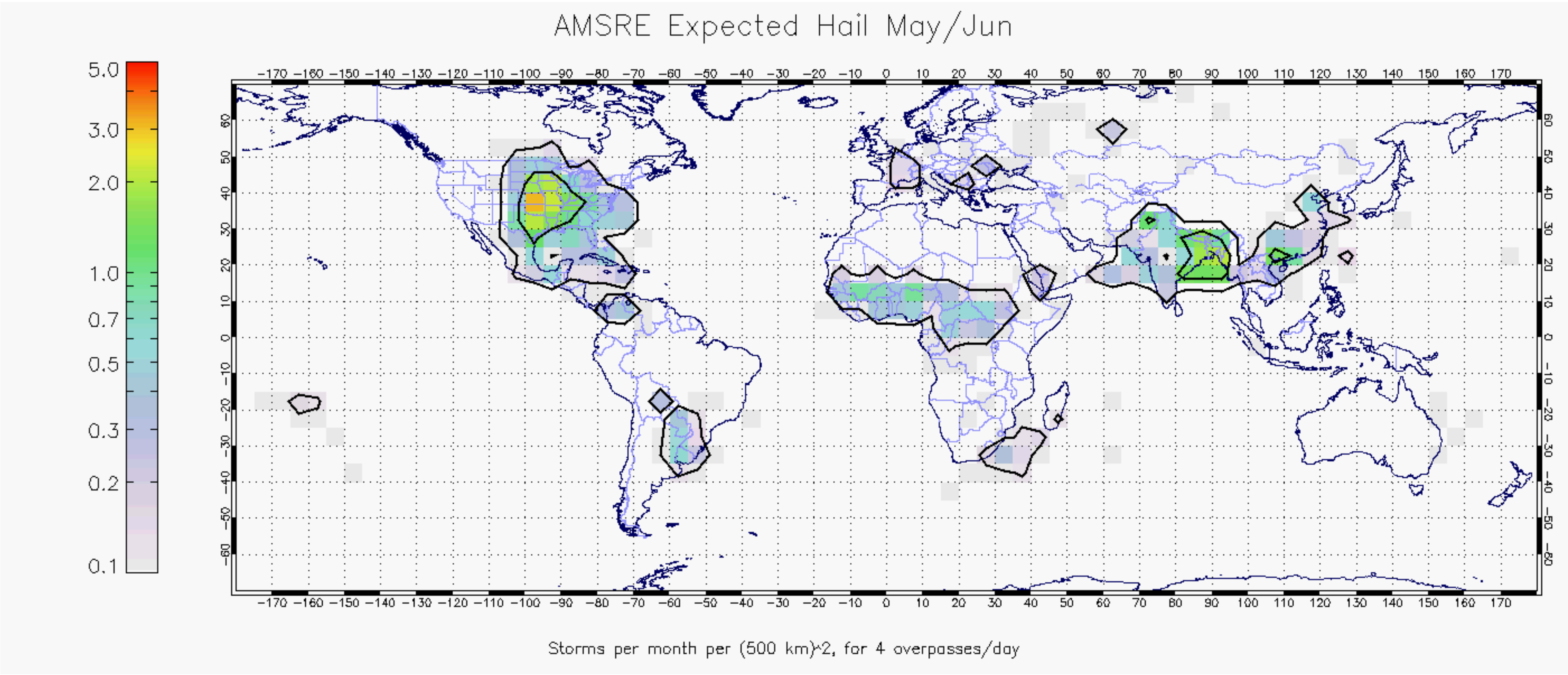
January - February



March - April

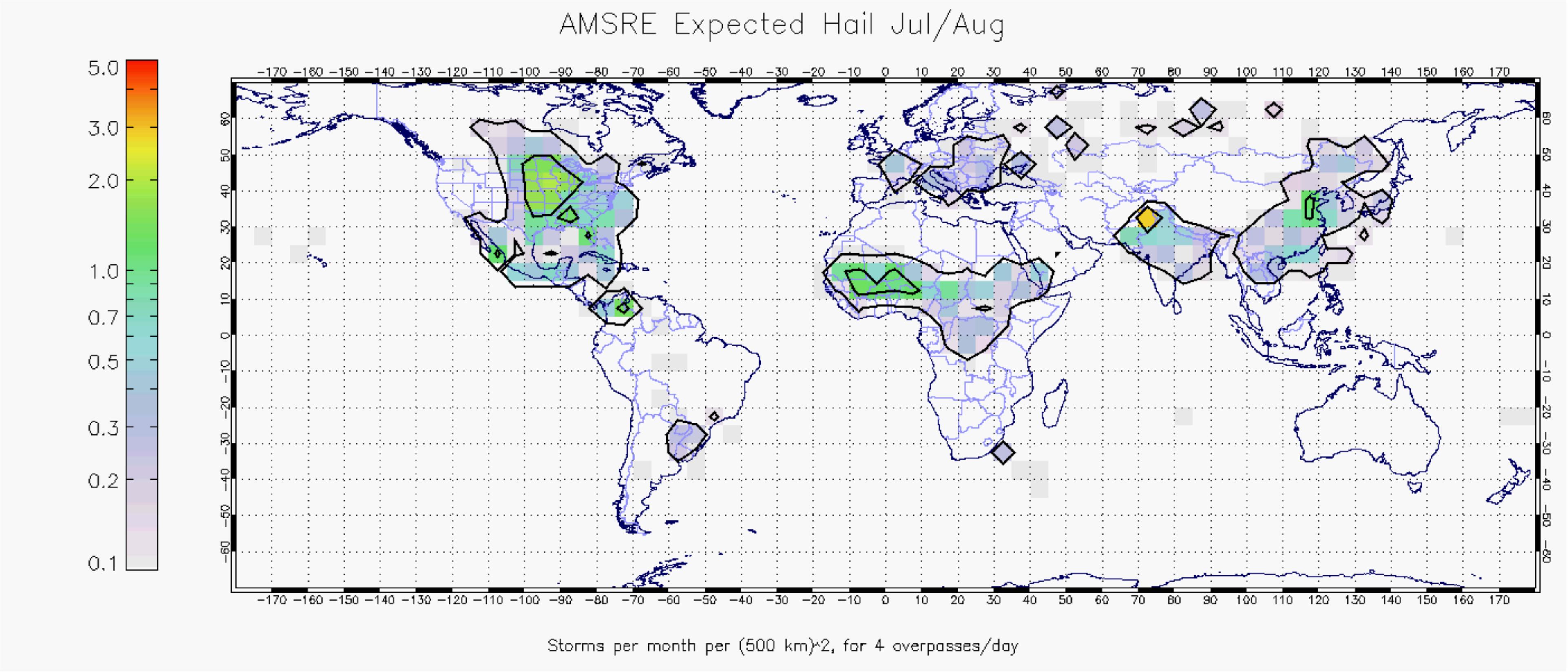

AMSRE Expected Hail Mar/Apr
5.0
3.0
2.0
1.0
0.7
0.5
0.3
0.2
0.1
Storms per month per (500 km)^2, for 4 overpasses/day

May - June

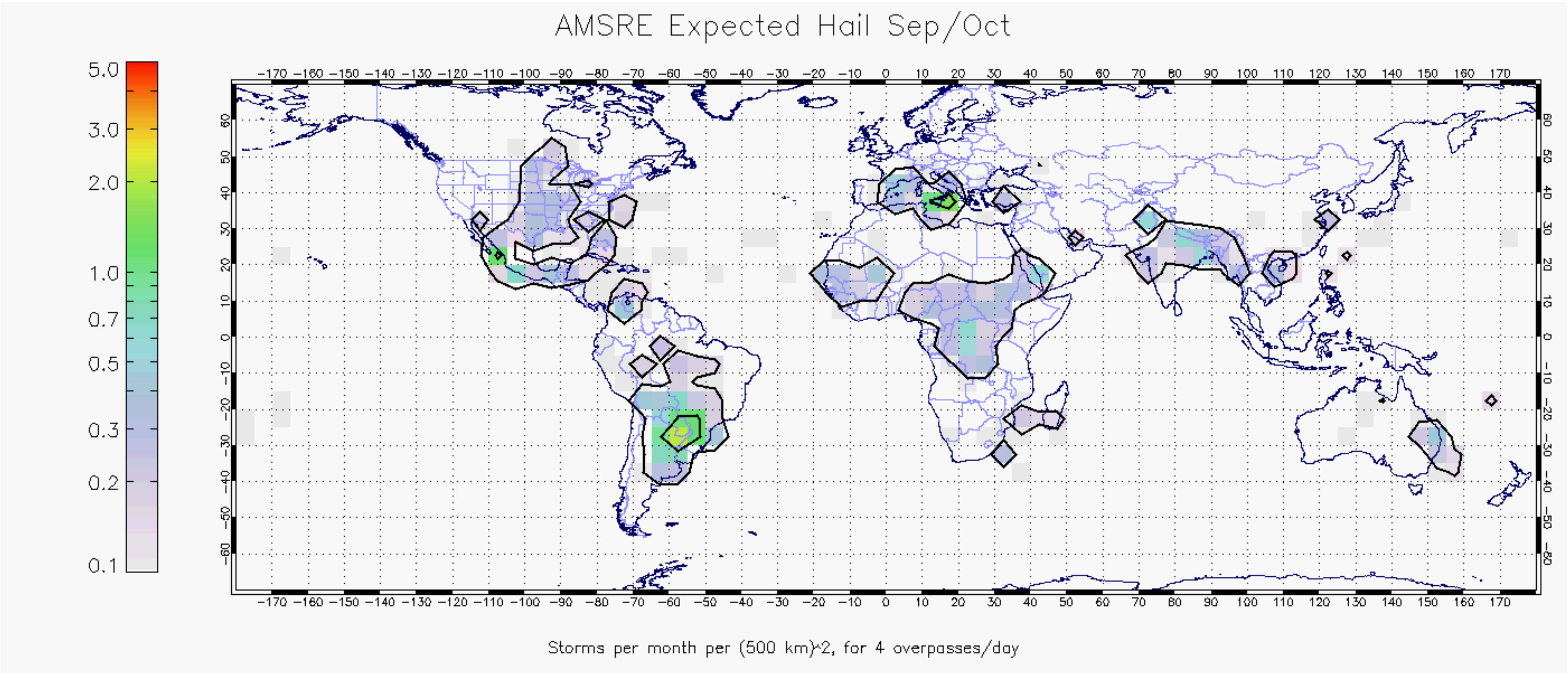


AMSRE Expected Hail May/Jun
5.0
3.0
2.0
1.0
0.7
0.5
0.3
0.2
0.1
Storms per month per (500 km)^2, for 4 overpasses/day

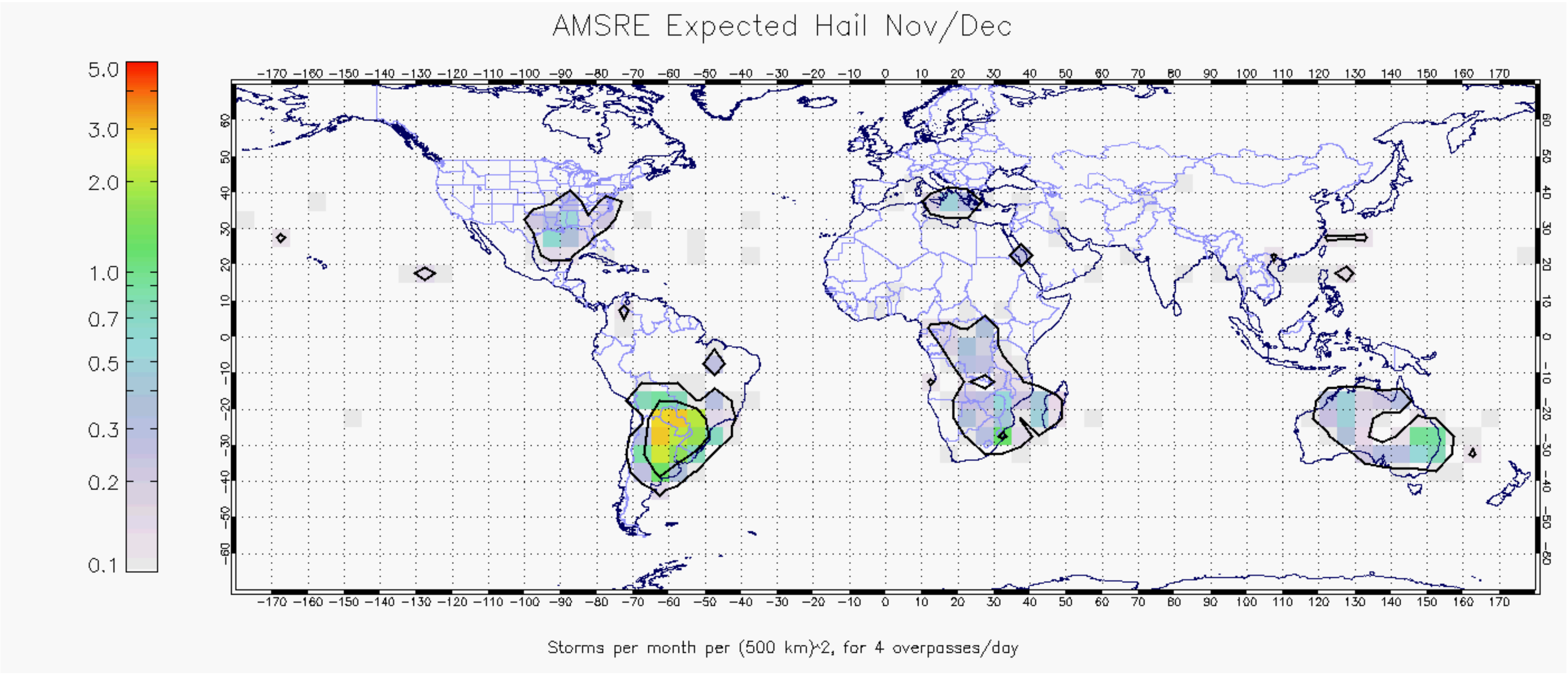
July - August


AMSRE Expected Hail Jul/Aug
5.0
3.0
2.0
1.0
0.7
0.5
0.3
0.2
0.1
-170 -160 -150 -140 -130 -120 -110 -100 -90 -80 -70 -60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170
60 50 40 30 20 10 0 -10 -20 -30 -40 -50 -60
Storms per month per (500 km)^2, for 4 overpasses/day

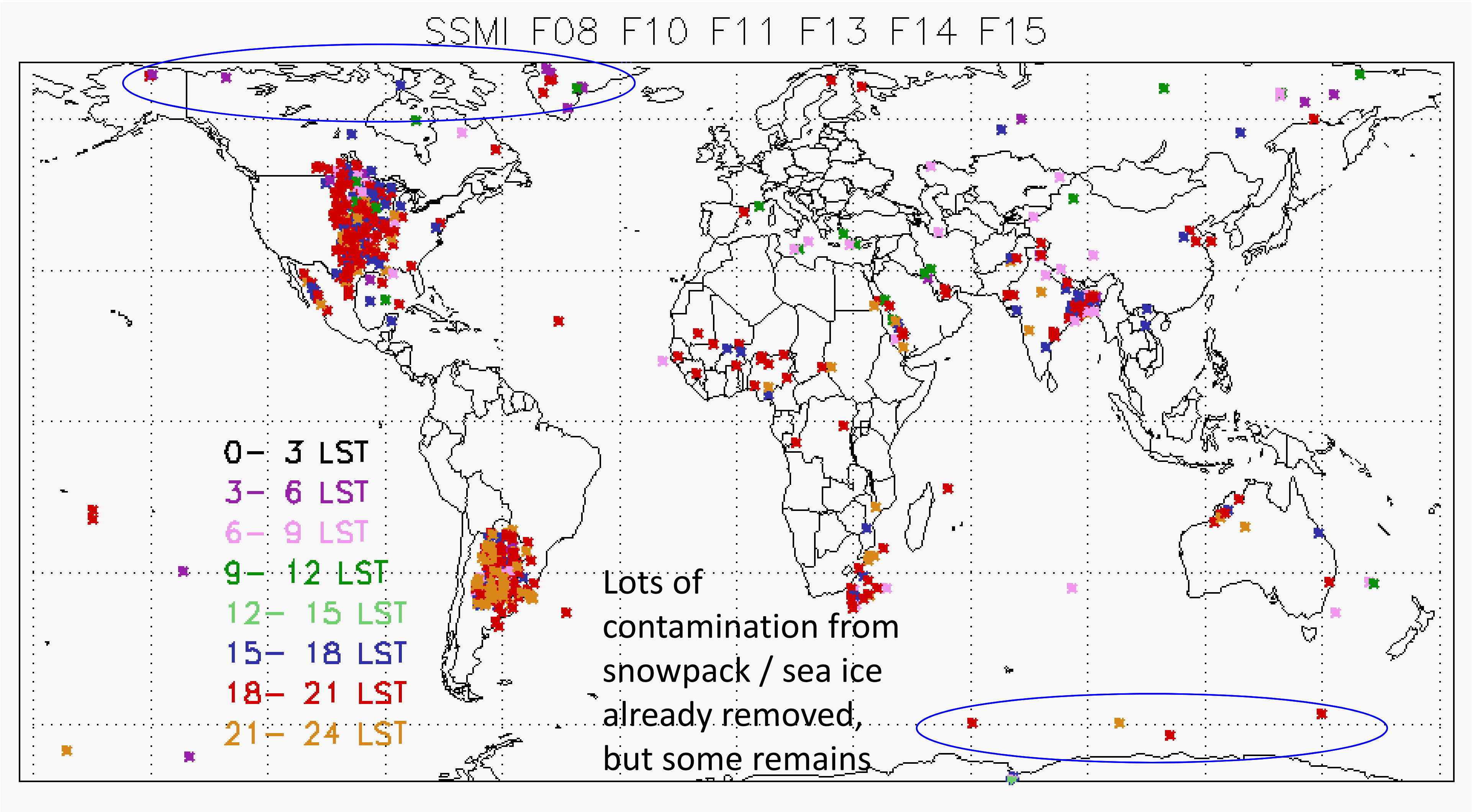
September - October



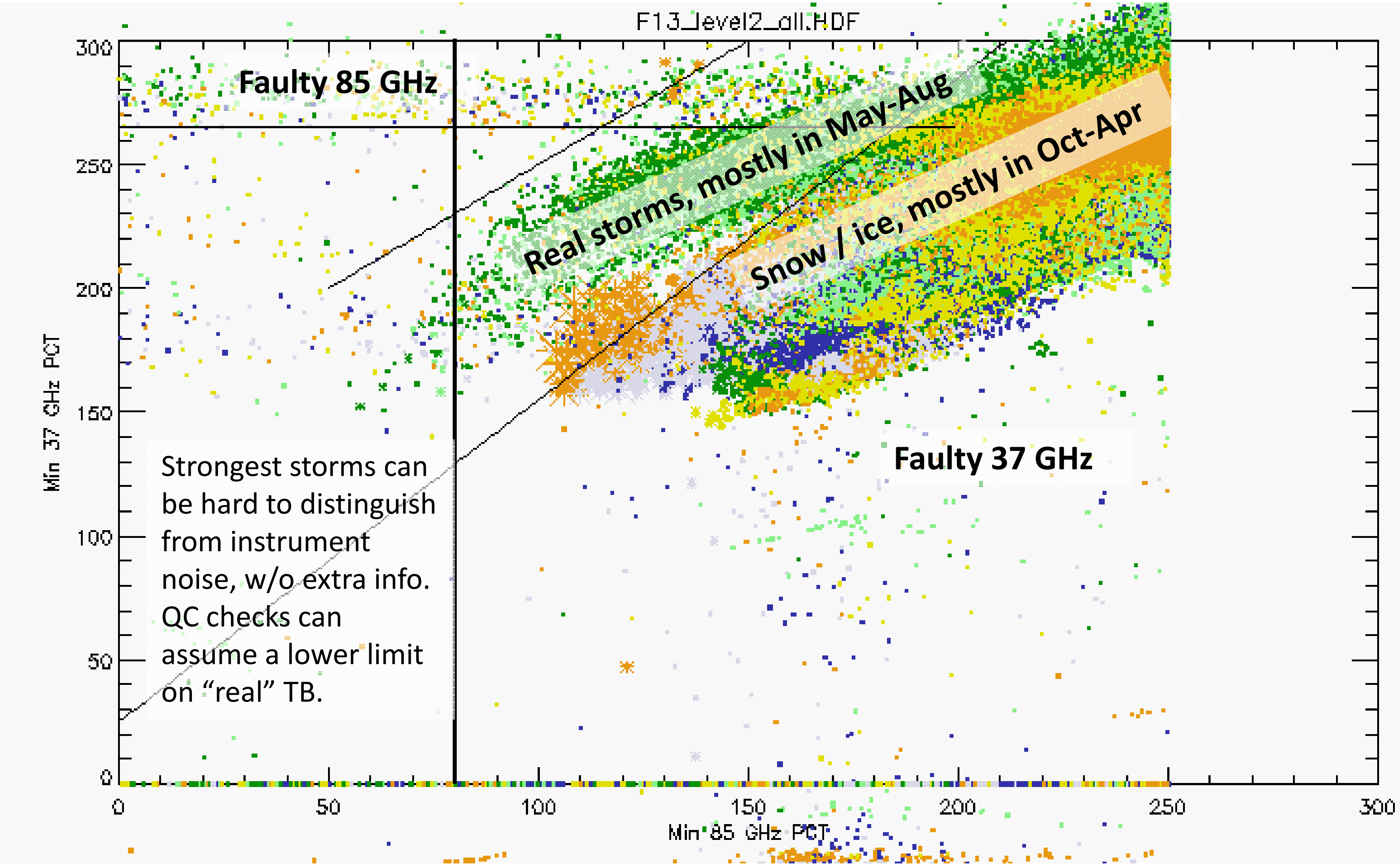
November - December



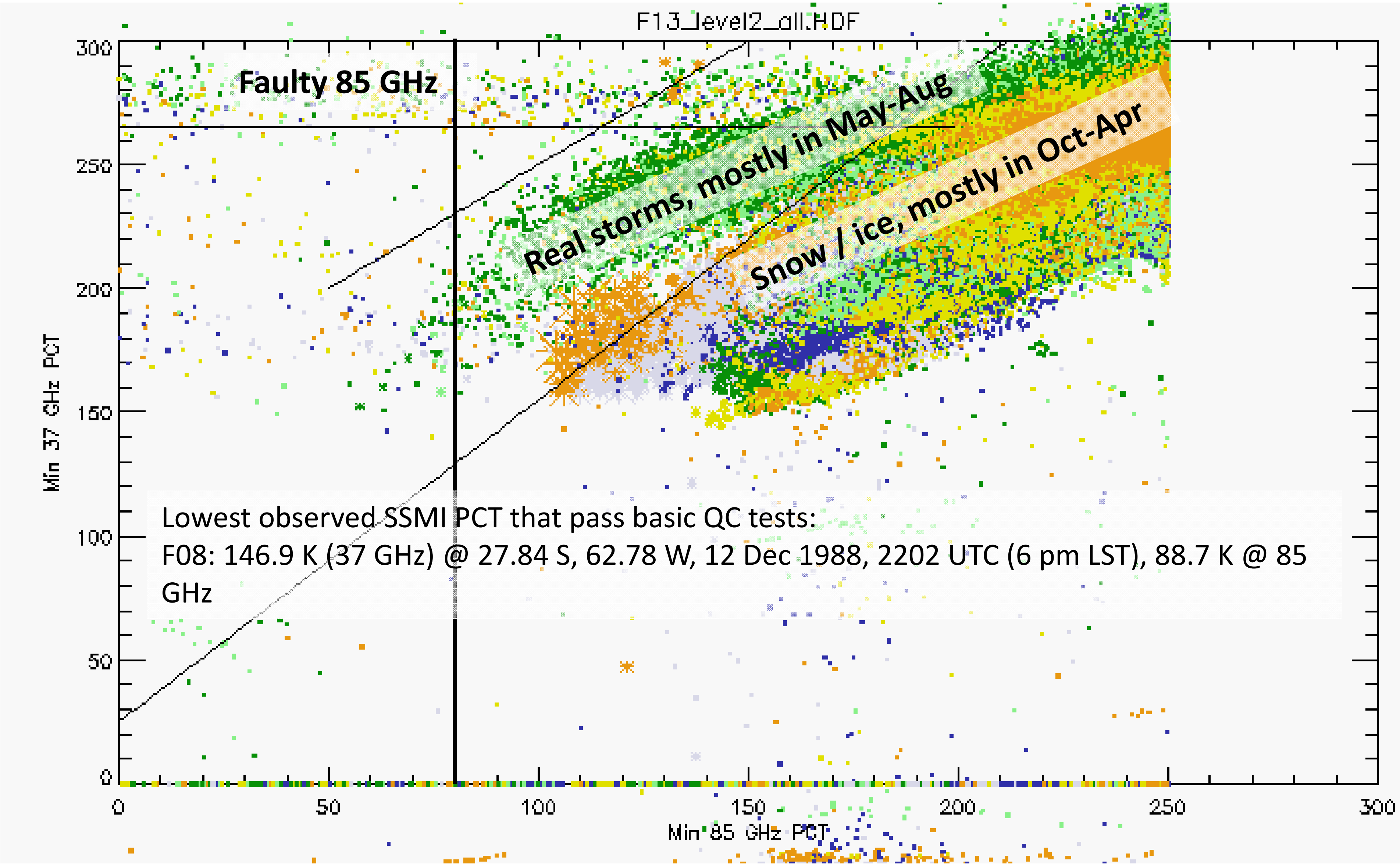
Simplified version using > 20 years of SSMI satellite data



SSMI – Sorting Signal from Noise



SSMI – Sorting Signal from Noise



Lowest observed SSMI PCT that pass basic QC tests:

F08: 146.9 K (37 GHz) @ 27.84 S, 62.78 W, 12 Dec 1988, 2202 UTC (6 pm LST), 88.7 K @ 85 GHz
F10: 120.9 K (37 GHz) @ 26.72 S, 61.25 W, 22 Dec 1991, 0104 UTC (9 pm LST), 64.5 K @ 85 GHz
F11: 119.1 K (37 GHz) @ 43.78 N, 92.67 W, 28 Jun 1998, 0026 UTC (9 pm LST), 63.4 K @ 85 GHz
F13: 129.2 K (37 GHz) @ 23.01 S, 63.46 W, 16 Nov 1998, 2205 UTC (6 pm LST), 51.0 K @ 85 GHz
F14: 123.8 K (37 GHz) @ 47.02 N, 94.22 W, 04 Jul 1999, 1507 UTC (9 am LST), 64.9 K @ 85 GHz

F08: too noisy in 85 GHz channel to determine
F10: 60.8 K (85 GHz) @ 16.07 S, 116.11 E, 30 Dec 1996, 1455 UTC (11 pm LST), 187.4 K @ 37 GHz
F11: 63.4 K (85 GHz) @ 43.78 N, 92.67 W, 28 Jun 1998, 0026 UTC (9 pm LST), 119.1 K @ 37 GHz
F13: 51.0 K (85 GHz) @ 23.01 S, 63.46 W, 16 Nov 1998, 2205 UTC (6 pm LST), 129.2 K @ 37 GHz
F14: 58.3 K (85 GHz) @ 27.93 S, 62.22 W, 30 Dec 1997, 0046 UTC (9 pm LST), 129.4 K @ 37 GHz

4 of these are Argentina, in Nov-Dec
2 of these are Minnesota, in June-July *(tornado reported with 4 July 1999 case)*
1 of these is Indian Ocean (NW of Australia), in Dec

The F14 case with its lowest 85 GHz is the same case as the TRMM example shown earlier, with TRMM's lowest-ever 37 GHz.

F14 measured 58 K @ 85 GHz, 129 K @ 37 GHz.
TRMM measured 45 K @ 85 GHz, 69 K @ 37 GHz 40 minutes later.

Summary

- Empirical relationships are used to estimate global hail climatology from satellites
- Most common locations:
  - ➢ N. Argentina, Paraguay, Uruguay, S. Brazil
  - ➢ East and West India, Bangladesh, Pakistan
  - ➢ Central and SE USA
  - ➢ Central Africa

- There are indications SE South America, Bangladesh, and Central Africa may be over-estimated by satellite

Summary

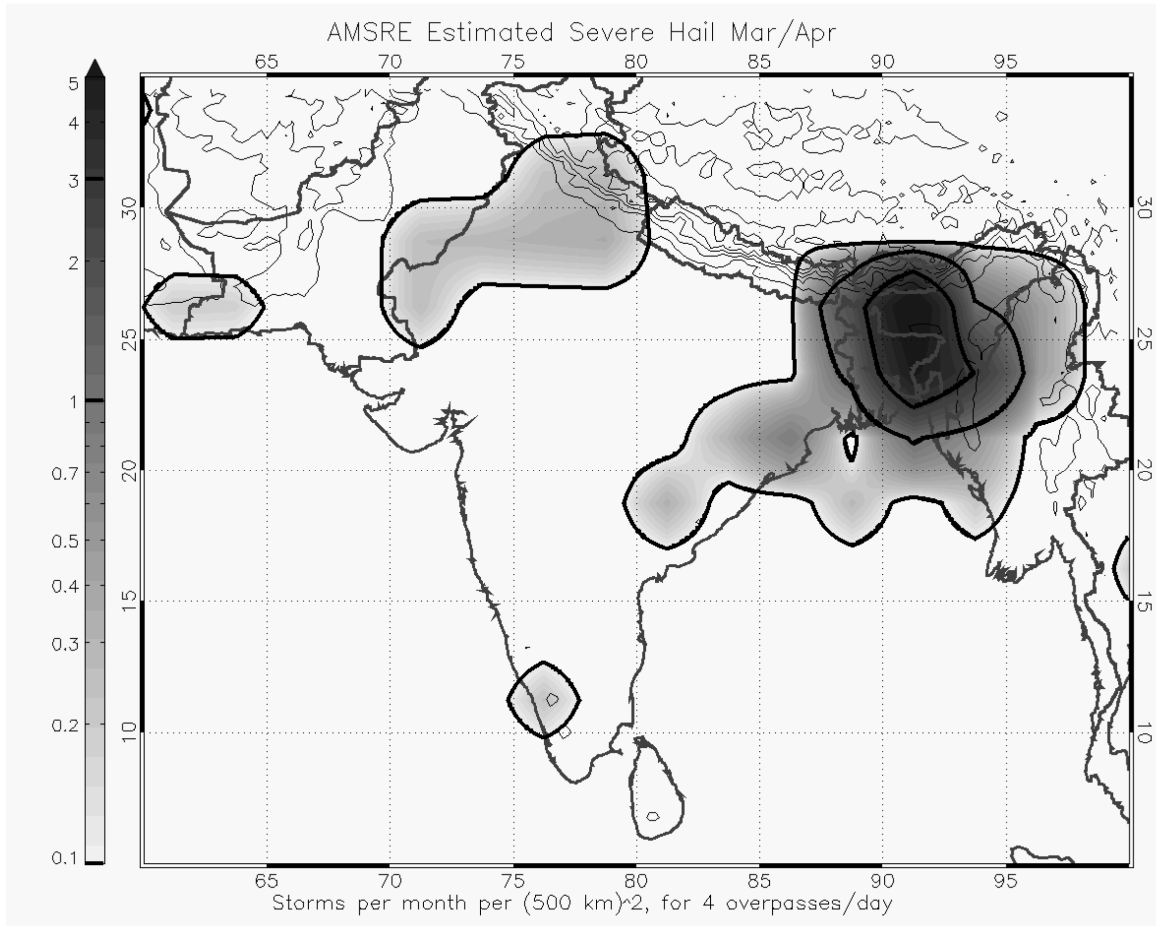
- The most active regions usually peak in late spring or early summer, with active area expanding poleward in summer

- Seasonality around India is more unique. East India and Bangladesh have frequent storms before monsoon begins in early June. After monsoon onset, convection weakens in the east (though rain is plentiful). Convection becomes more intense in the west, near Pakistan by July-August.

Indian Subcontinent – March - April

Many hailstorms in spring / pre-monsoon season in East India & Bangladesh

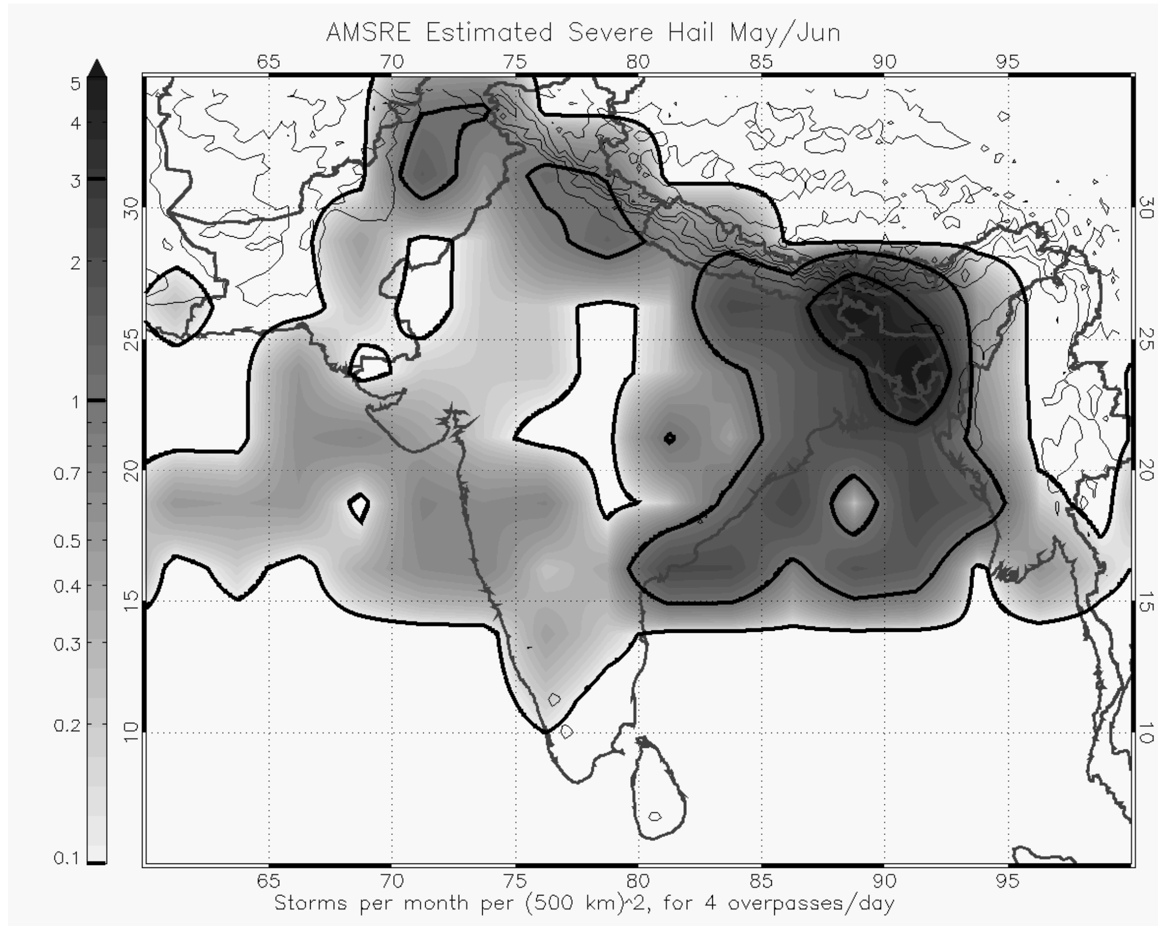
Activity abruptly shifts west toward Pakistan after monsoon onset in early June



Indian Subcontinent – May - June

Many hailstorms in spring / pre-monsoon season in East India & Bangladesh

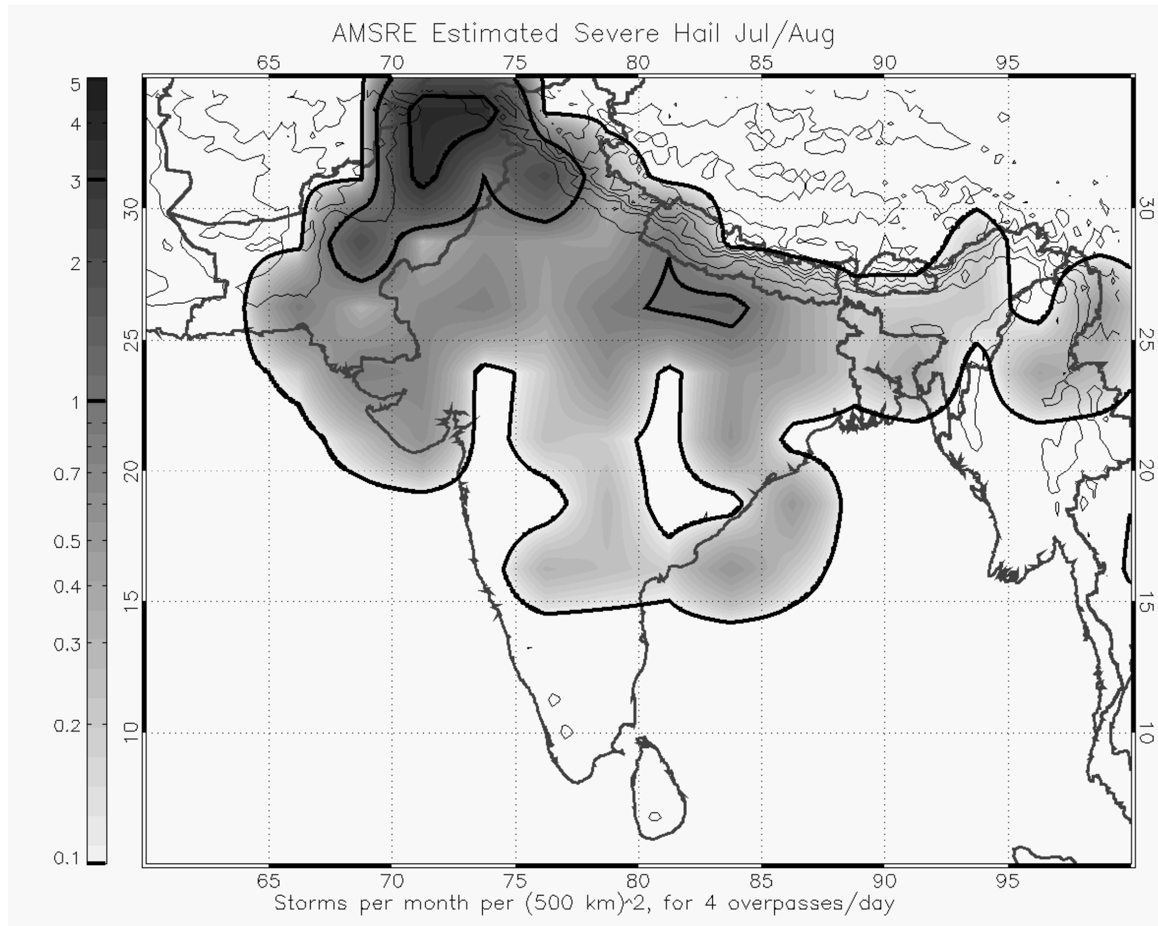
Activity abruptly shifts west toward Pakistan after monsoon onset in early June



Indian Subcontinent – Sept. – Oct.

Many hailstorms in spring / pre-monsoon season in East India & Bangladesh

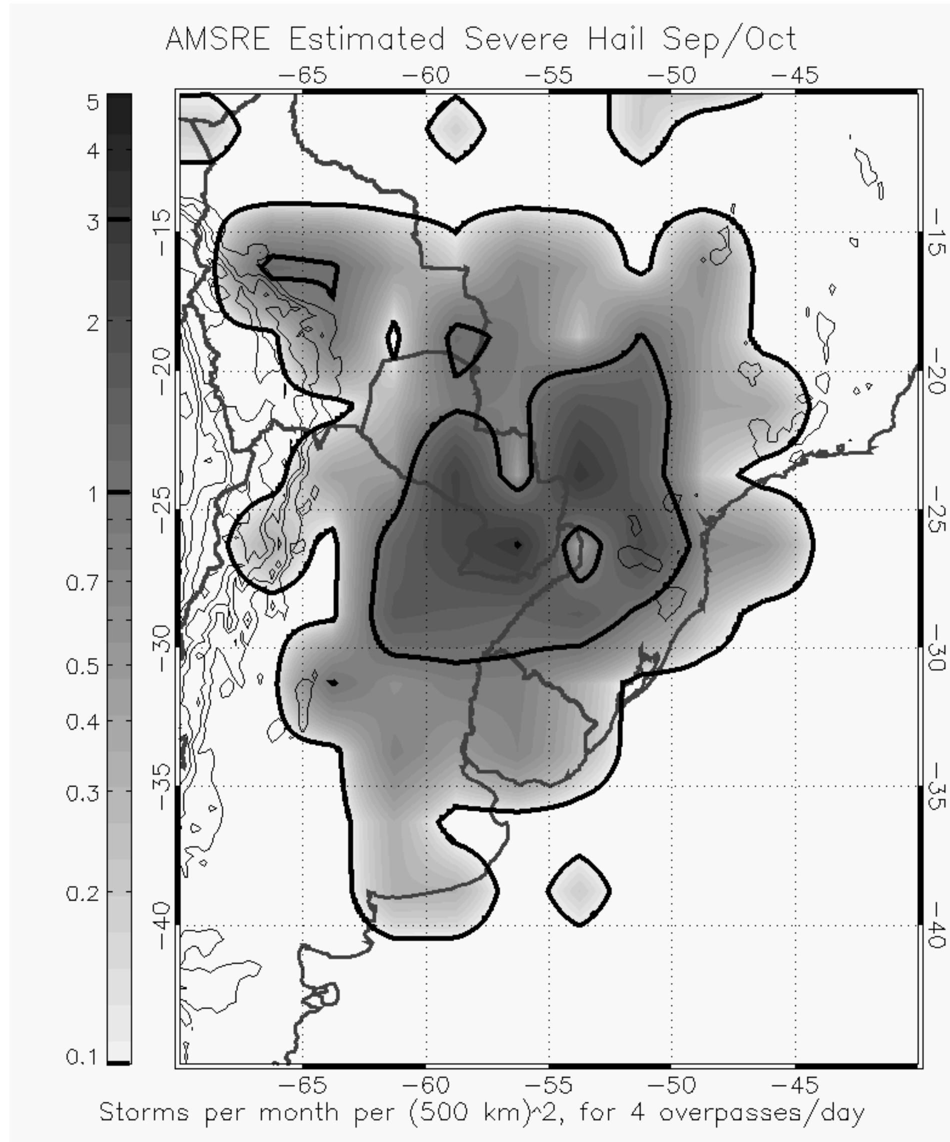
Activity abruptly shifts west toward Pakistan after monsoon onset in early June



SE South America– Sept. – Oct.

Hail storm locations shift from Paraguay and Southern Brazil in early spring to Northern Argentina in late spring and summer.

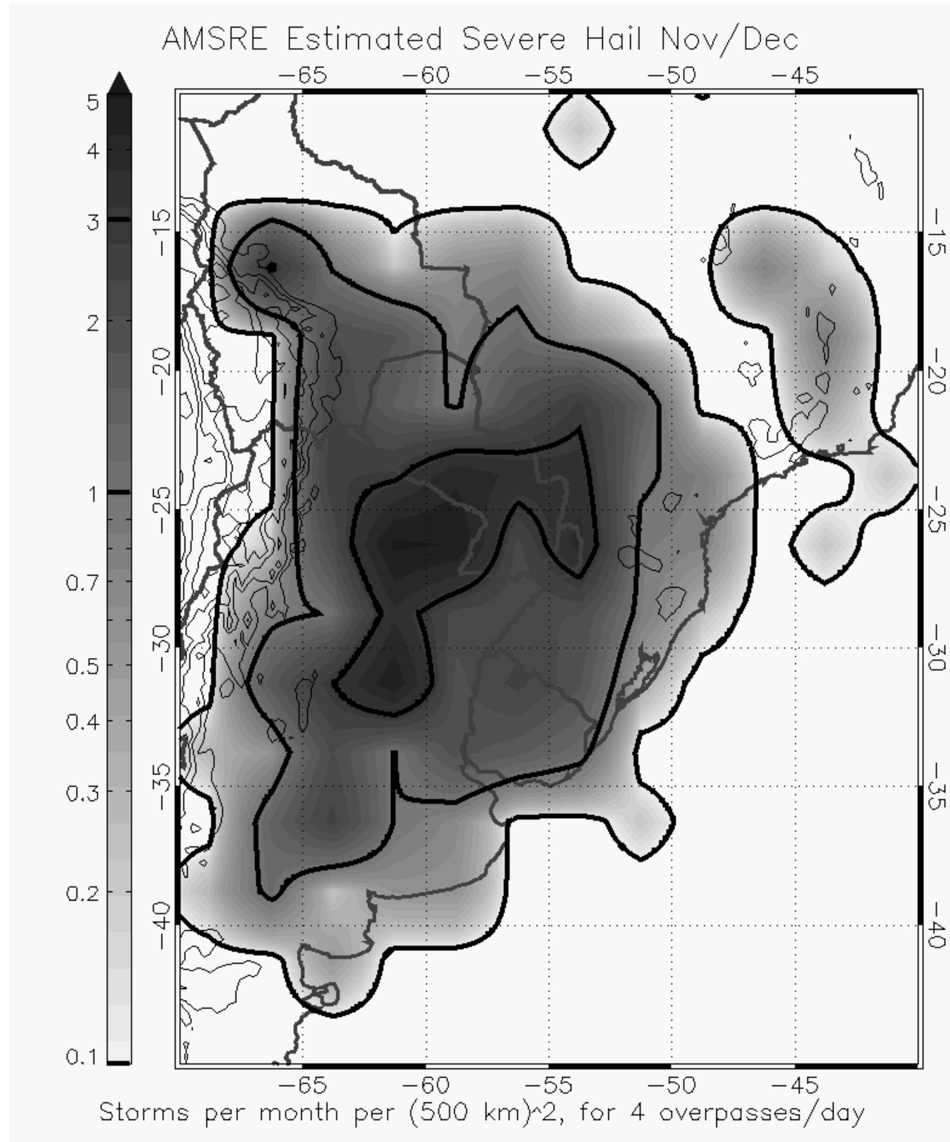
Surface observations suggest the true locations should be further west and south (?)



SE South America– Nov. - Dec.

Hail storm locations shift from Paraguay and Southern Brazil in early spring to Northern Argentina in late spring and summer.

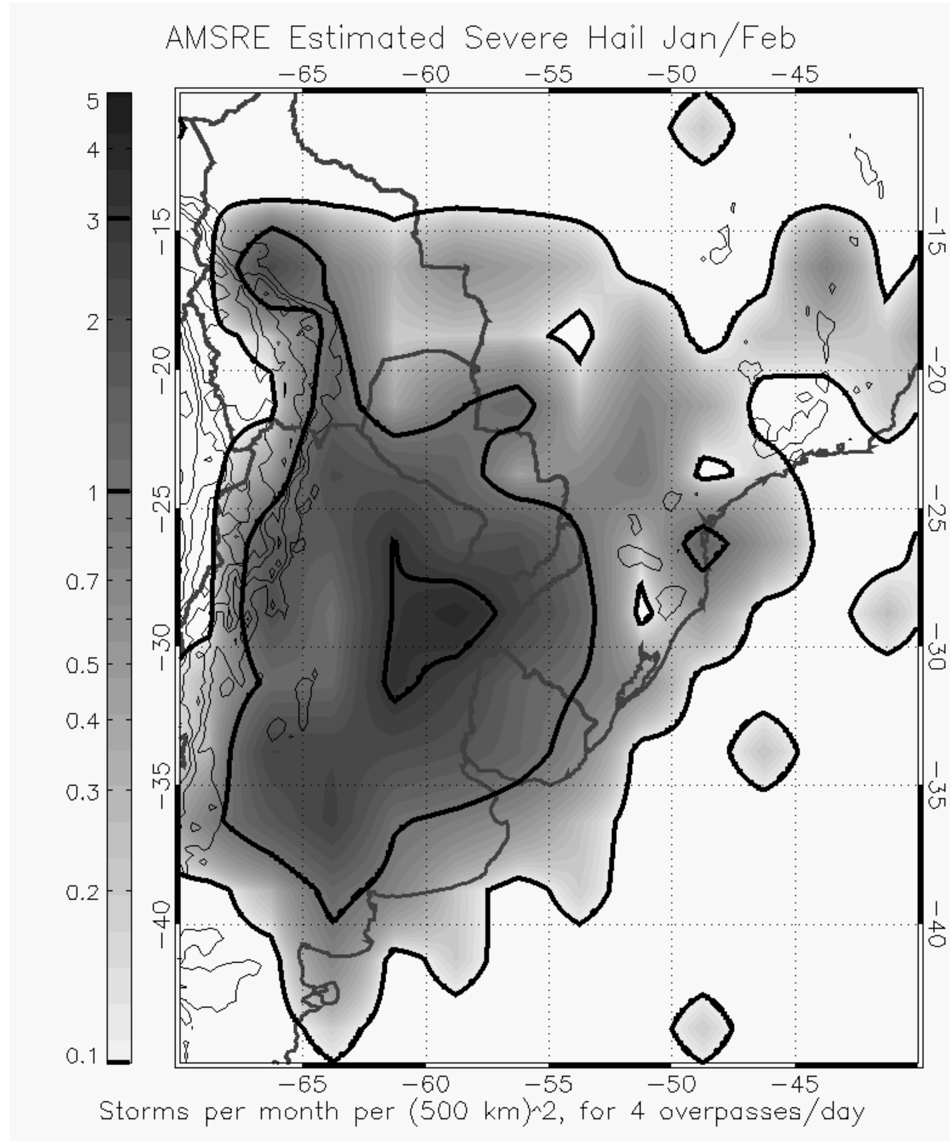
Surface observations suggest the true locations should be further west and south (?)



SE South America– Jan - Feb.

Hail storm locations shift from Paraguay and Southern Brazil in early spring to Northern Argentina in late spring and summer.

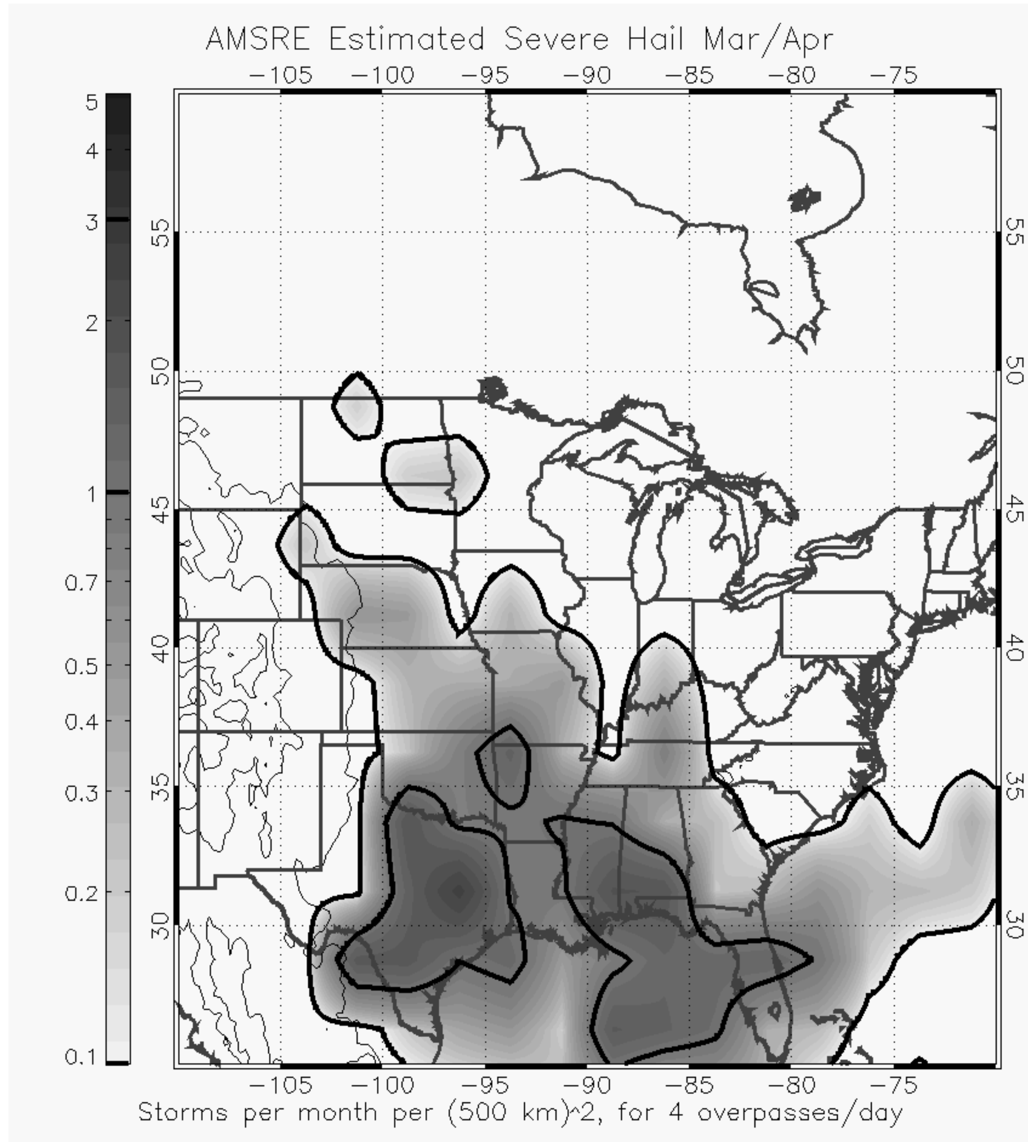
Surface observations suggest the true locations should be further west and south (?)



North America – March - April

Cool season storms mostly confined to southeast and south-central USA.

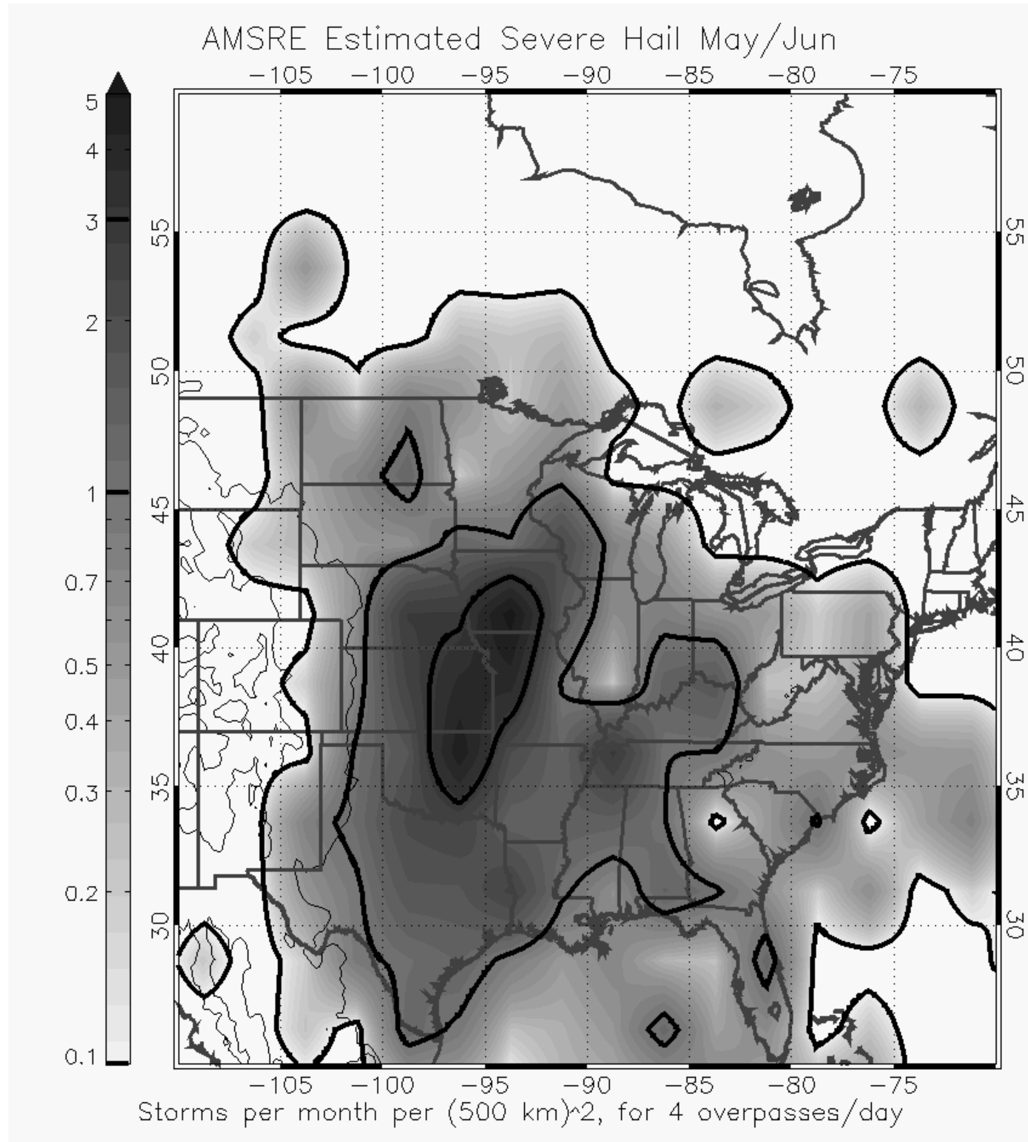
Activity expands northward through Central Plains, into Canada during summer



North America – May - June

Cool season storms mostly confined to southeast and south-central USA.

Activity expands northward through Central Plains, into Canada during summer



North America – July - August

Cool season storms mostly confined to southeast and south-central USA.

Activity expands northward through Central Plains, into Canada during summer